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Investigating causes of changes in runoff using hydrological simulation approach

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Abstract Stream flow plays a crucial role in environmental, social and economic contexts. It is of significance to investigate the causes of change in runoff for better water resources management. This study detects the variation trend of recorded runoff of the Gushan River, a tributary of the Yellow River located on the Loess Plateau with severe soil and water losing, and investigates the impacts of climate change and human activities on runoff using hydrological simulation approach. Results show that the recorded runoff at Gaoshiya station on the Gushan River has experienced a significant declining trend from 1954–2013 with an abrupt change occurring in 1973. SimHyd rainfall runoff model performs well for monthly discharge simulation with Nash–Sutcliffe coefficient of 82.6 % and relative error of 0.32 %. Runoff depth over the catchment in 1980–2013 reduced by 52.4 mm compared to the previous period, in which human activities and climate change contribute 61.5 and 38.5 % of the total runoff reduction, respectively. However, the human-induced impact tends to increase. Therefore, efforts to improve the ecology of the Loess Plateau should give sufficient attention to the impacts of human activity.

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Introduction

Water is a fundamental element for supporting human life as well as ecological systems, which is therefore of crucial importance in environmental, social and economic contexts, particularly for the arid area (Li and Sheng 2011). Variability of stream flow presents a challenge to the security of water supply and thus has attracted loads of attention from local communities (Zhang et al. 2013).

Due to climate change and intensive human activities in recent decades, the runoff of many rivers in the world has been changing. About 22 % of the world's rivers were shown to have a significant decrease in annual runoff because of increasing water consumptions and diversion (Walling and Fang 2003). Recorded runoff series from 1950 to 2010 of six major rivers in China were characterized by a general decreasing trend with significant decrease trends occurring in the northern major rivers (Wang et al. 2013). For example, the Yellow River ran dry for 226 days in 1997. It has experienced continuously declining in runoff during the recent decades, which has resulted in huge economic loss and brought a great challenge to water resources and environmental management (Zhang and Wang 2014).

Climate dominates regional hydrological regime. Changes in precipitation and temperature have, therefore, direct influences on stream flow (Zhang and Wang 2007). McFarlane et al. (2012) used GCM projections to simulate water yields in south-western Australia over the coming decades and found the surface water yields might decrease by 24 % due to climate change. Wang et al. (2016)

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investigated the sensitivity of stream flow to hypothetical climate changes in climatically different climate zones in China, and found runoff is highly sensitive to changes of precipitation and temperature. Previous studies indicate that 10 % change in precipitation will result in 15–25 % change in runoff, whereas a 2 °C rise in temperature will lead to 5–12 % decrease in runoff (Roger et al. 2005; Jones et al. 2005; Benedikt et al. 2007; Lorena et al. 2010; Bao et al. 2012a; Wang et al. 2016). Human activities, such as land cover change, urbanization, and water conservation projects, impose significant impacts on runoff through changing the runoff generation condition and therefore altering the regional hydrologic cycle (Zhang and Wang 2014). The current extent human land cover change has increased global runoff by 7.6 % and reduced global annual average terrestrial evapotranspiration by 5 % which is approximately equivalent in volume to annual global water withdrawals (Shannon et al. 2013). Water consumption for agriculture and industry has direct impacts on runoff through pumping water from stream for irrigation and meeting demand of industry. Water consumption for agriculture accounts for over 70 % of total water consumption in China (Zhang 2005). Climate change and human activities are impacting runoff simultaneously. In this context, separating and quantifying the contributions of climate change and human activities to runoff changes are a challenging problem (Wang et al. 2008).

In recent years, hydrologists have made great efforts to attribution analysis of changes in runoff (Wang et al. 2008; Bao et al. 2012b; Zhang and Wang 2014). The traditional approaches to study the impacts of human activities on stream flows are based on field investigation and hydrological experiments which usually cost huge of human and financial resources (Xu et al. 2009; Zhang and Wang 2014). Hydrological models have been often used for investigating the impacts of climate change on runoff changes in recent years (Wang et al. 2012; Hidalgo et al. 2013; Arnell and Gosling 2013; Szepszo et al. 2014). Typically, Wang et al. (2008) applied a simple water balance model to the Sanchuan River catchment to naturalize the runoff in human-disturbed period and regarded the difference between naturalized runoff and recorded runoff as the contribution induced by human activities to runoff change. The above method was further applied to other catchments by many other hydrologists (Bao et al. 2012b; Zhan et al. 2013; Ma et al. 2014; Guo et al. 2014). For example, with the method, Ma et al. (2014) found climate change has led to a stream flow increase of 40.8 m^3/s per year for the Huai River basin, while human activities have resulted in a stream flow decrease of 33.51 m^3/s per year. Moreover, studying the drivers of changes in runoff of the Luan River over the period of 1958–2008, Zeng et al. (2015) found climate-induced runoff reduction accounted

for 28.3–46.8 % of the total runoff reduction while human activities played a principal role in decreases of runoff.

The Loess Plateau is located in semi-arid climate zone where water shortage is a main water issue due to dry climatic condition. It was reported that streams run dry for most rivers on the Loess Plateau, particularly in dry seasons (Xu et al. 2009). It is of significance to investigate quantitatively reasons of decreases in runoff for water resources management of the Loess Plateau. Taking the Gushan River, the most typical river catchment on the Loess Plateau with severe soil and water losing, as a case, the objectives of this study are: (1) to detect the variation trend of runoff series of the Gushan River and identify the natural period of runoff series, (2) to investigate the principal drivers of runoff variation, and then quantitatively evaluate the contribution of climate change and human activities to changes in runoff of the Gushan River.

Data and methods

Description of the Gushan River catchment

The Gushan River is the first-order tributary of the middle Yellow River, originating from Tanger Banner of the Inner Mongolia. The main stream runs eastward to join the Yellow River at Fugu county of Shaanxi province. The drainage area of the catchment is 1,263 km^2 with a main stream length of 79.4 km. Gaoshiya station is the most downstream hydrometric station on the Gushan River, established in 1953. Four well-gaged rainfall stations within the catchment with a long record were selected. The locations of the rainfall stations and the Gaoshiya hydrometric station are shown in Fig. 1.

The Gushan River catchment is in the East Asia Monsoon climate zone and is characterized by low precipitation and high potential evaporation. The distribution of precipitation is highly uneven in time and space. Due to dry climate condition, thick porous soil layer, sparse vegetation coverage and high-intensity rain storm, the Gushan River is short of water resources and heavy in soil erosion. The multiple-year average annual runoff and sediment yield at the Gaoshiya station are 67.85 million m^3 and 19.2 million t, among which over 70 % of the annual runoff and over 80 % sediment yield are from flood seasons from July to September.

Major human activities (i.e., soil and water conservation measures) have attempted to combat with severe soil and water losses, with the most intensive activities emerging since the late of 1970s. As of 2011, local citizens had constructed 2 substantial dams on the main stream with total storage capacity of 5.3 million m^3, 852 check dams on tributaries with total controlled area of over 61 km^2. The
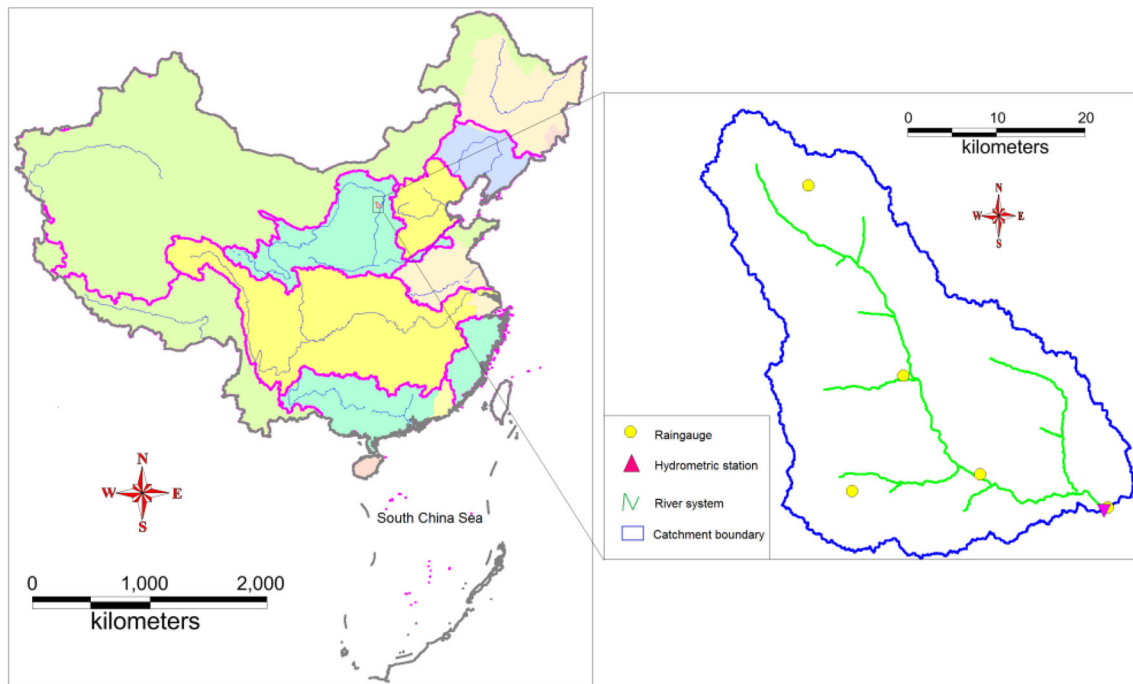
Fig. 1 River system and locations of rain gauges and the Gaoshiya hydrometric station of the Gushan River catchment

implemented soil and water conservation measures in the catchment include 39.54 km^2 of terraced land, 15.78 km^2 of newly formed dam-land, 370.1 km^2 of forestation, and 174.4 km^2 of grassland (NBSC 2013). Substantial dams and check dams could affect runoff directly by storing water in reservoirs. However, the other soil and water conservation measures (e.g. terracing land, reforestation, etc.) have indirect impacts on runoff by changing land cover.

Quantitative method for attribution analysis of runoff change

Intensive human activities will lead to an abrupt change in runoff series. Taking runoff before the abrupt change point as the baseline, the difference between the runoff after the change point and the baseline includes two parts, human-induced runoff change and climate-induced runoff change. Hydrological model is usually calibrated with data series in natural period and then employed to naturalize runoff in human-disturbed period. The difference between recorded runoff and naturalized runoff in human-disturbed period is induced by human activities (Wang et al. 2008).

Using the hydrological simulation approach to analyze attribution of runoff change, one key step is the selection of baseline which is often regarded as a natural period of a runoff series before abrupt change. Sequential Cluster Analysis is a commonly used statistical method to detect abrupt change point of runoff series by pursuing the minimum sum of squared deviations Sn(t) for the series before and after the abrupt change point, viz. Sn*(t) = min [Sn(t)] (Wang et al. 2008; Zhang and Wang 2014).

Hydrological model could be used to detect abrupt change of s runoff series by analyzing simulation errors of hydrological processes. Wang et al. (2015) proposed a simulation-based method for the detection of a natural epoch in a runoff series using hydrological modeling. The method assumes that human activities will lead to systematic simulation errors of hydrological processes, thus the accumulated standard simulation errors Sum(t) will continuously increase or decrease after an abrupt change point in a runoff series induced by human activities. The abrupt change induced by human activities will occur at a point, after which Sum(t) will be continuously greater or less than zero. The time series before the point could then be treated as a natural series.

In this study, both Sequential Cluster Analysis and simulation-based abrupt change detection method were employed to diagnose natural period of runoff series.

Description of SimHyd rainfall runoff model

Conceptual hydrological models are useful in assessing the impacts of environmental changes on regional hydrology (Wang et al. 2008; Bao et al. 2012a). In this paper, we employed SimHyd rainfall runoff model which has already been applied successfully in some semi-arid or semi-humid basins located in the USA, Australia, and other countries to

naturalize stream flow (Chiew et al. 2002; Wang et al. 2015). The structure of the SimHyd model is shown in Fig. 2.

The SimHyd model estimates daily or monthly stream flow from daily or monthly rainfall and potential evaporation (Pan evaporation) data. The model divides runoff into three components: surface flow, interflow, and base flow. The surface flow is infiltration excess runoff. Interflow is estimated as a linear function of the soil wetness. Base flow is simulated as a linear recession from the groundwater store. The infiltration rate is a core of the model and expressed as a negative exponential function of soil wetness.

Evapotranspiration losses include two parts: the first part is from interception of vegetation cover and is calculated with the potential evaporation rate; the second part is from soil moisture storage and estimated as a linear function of the soil wetness, but cannot exceed the atmospherically controlled rate of areal potential evapotranspiration.

There are seven hydrological parameters in the model that need to be calibrated with recorded daily or monthly stream flow (Table 1). Plenty of measures are available to evaluate model performance, among which the Nash–Sutcliffe efficiency coefficient (NSE) and the relative error of volumetric fit (RE) are the most effective ones and have been widely applied in practices for model calibration (Nash and Sutcliffe 1970; Zhang and Wang 2007). A good simulation result will have NSE close to 1 and RE close to 0. The two measures are expressed mathematically as follows:

$$\text{NSE} = 1 - \frac{\sum\limits_{i=1}^{N} (Q_{oi} - Q_{ai})^2}{\sum\limits_{i=1}^{N} (Q_{oi} - \overline{Q_{oi}})^2} \qquad (1)$$

$$\text{RE} = \sum_{i=1}^{N} (Q_{ai} - Q_{oi}) \bigg/ \sum_{i=1}^{N} Q_{oi} \times 100\,\% \qquad (2)$$

where Q_{oi} and Q_{ai} are observed and simulated runoff in month i, respectively; N is the number of all samples; $\overline{Q_{oi}}$ is multiple-year average of recorded runoff.

Results and discussion

Inter-annual variability of precipitation, temperature and recorded runoff during 1954–2013

The Intergovernmental Panel on Climate Change (IPCC) series of reports concluded that global mean air temperature showed a significant increase during the past 50 years while only slight change occurred in global mean precipitation (IPCC 2013). The Gushan River catchment is located in the Eastern-Asia Monsoon climate zone, which is generally arid to semi-arid. The average areal annual precipitation over 1954–2013 is approximately 510 mm with a higher decadal variability. Long-term variations of annual precipitation and temperature in the Gushan River catchment from 1954 to 2013 are shown in Fig. 3.

Figure 3 indicates that the annual precipitation varies from 166 to 726 mm with a slightly decline trend of −1.378 mm/year over the period of 1954–2013. The annual mean temperature presents a significant rising trend of 0.015 °C/year for the whole period with an average of 8.12 °C and a variation range of 7.12–9.28 °C. Decrease in precipitation and rise in temperature with no doubt will lead to reduction in runoff.

The average annual runoff at the Gaoshiya hydrometric station over the period of 1954–2013 is 53.7 mm. Long-term variations of recorded runoff and its 5-year moving average process are shown in Fig. 4.

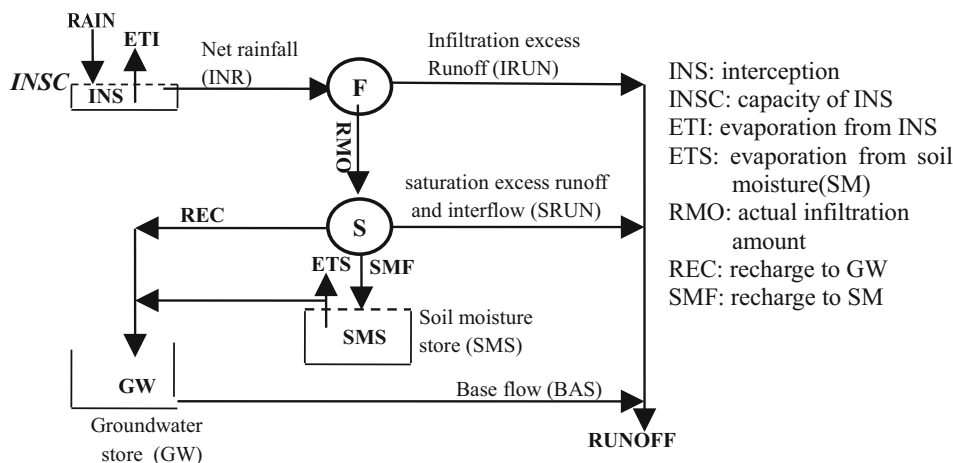Fig. 2 Schematic diagram of the SimHyd rainfall runoff model

INS: interception
INSC: capacity of INS
ETI: evaporation from INS
ETS: evaporation from soil moisture(SM)
RMO: actual infiltration amount
REC: recharge to GW
SMF: recharge to SM

Table 1 Calibrated model parameters of the Gushan River catchment

Model parameters	Description	Default minimum	Default maximum	Calibrated value
INSC	Interception store capacity/mm	0	10	3.2
COEFF	Maximum infiltration loss/mm	0	20	6.8
SQ	Infiltration loss exponent	0	1	0.3
SMSC	Soil moisture store capacity/mm	0	400	180
SUB	Constant of proportionality in interflow equation	0	1	0.13
CRAK	Constant of proportionality in groundwater recharge equation	0	1	0.24
K	Baseflow linear recession parameter	0	1	0.06

Fig. 3 Variations of annual precipitation and temperature of the Gushan River catchment over 1954–2013

$P = -1.3782\,t + 461.74$

$T = 0.015\,t + 7.6607$
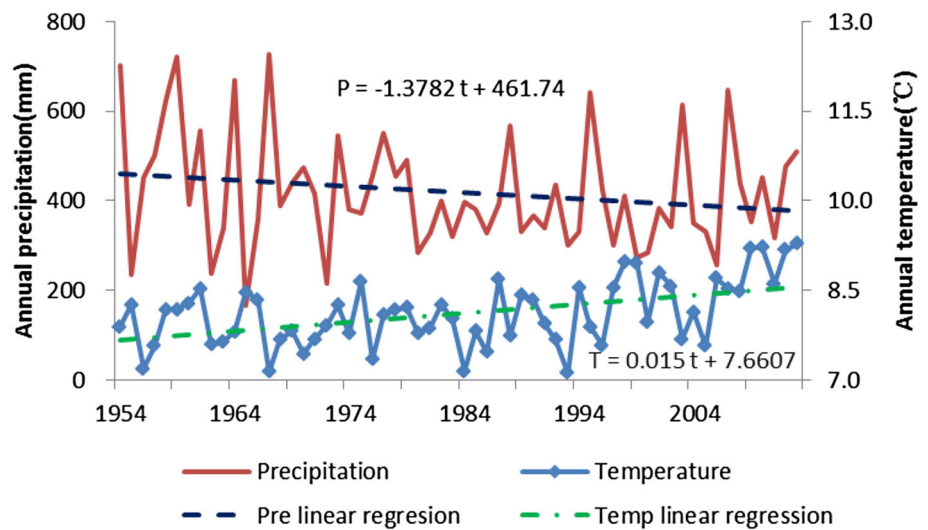
Fig. 4 Variations of annual runoff and its 5-year moving average process at Gaoshiya station from 1954 to 2013
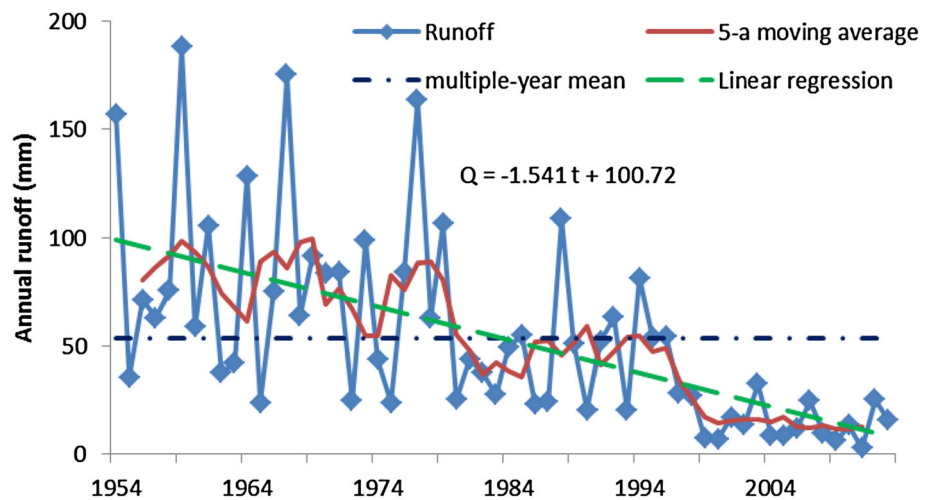
$Q = -1.541\,t + 100.72$

Figure 4 shows that (1) the recorded runoff presents a high variability with the range from 3.06 mm in 2011 to 188.0 mm in 1959. Most of the high runoff years occurred before 1980. The observed runoff has been continuously and unprecedentedly low since 2000. (2) Runoff series exhibits a significant decreasing trend with the linear decline rate of -1.541 mm/year. (3) According to the magnitude of recorded runoff, runoff series over the years of 1954–2013 could be visibly divided into three phases: higher flow period of 1954–1979, medium flow period of

1980–1999, and low flow period of 2000–2013. Abrupt change point of runoff series induced by human activities (e.g. reservoirs and check dams construction) may probably occur in 1980 according to roughly visual judgment.

Trend variation of runoff series results from changes in climate and land coverage (e.g. reforestation, terracing, and regressing, etc.) for most cases. However, abrupt change in runoff series was mostly induced by construction of reservoir and sharply increases in water consumption due to increasing agricultural irrigation and industrial demands.

Model calibration and baseline period selection

Sequential Cluster Analysis was employed to detect the abrupt change point of runoff series. The sum of squared deviations of annual runoff versus time is shown in Fig. 5. Figure 5 shows that the local minima occurred in 1980, indicating that 1980 is detected as abrupt change point of runoff series.

To ensure the consistency of the natural runoff data series, data series over 1954–1969 are used to calibrate the SimHyd rainfall runoff model (Table 1). The monthly simulated and recorded discharges at the Gaoshiya station over the period 1954–1969 are compared in Fig. 6.
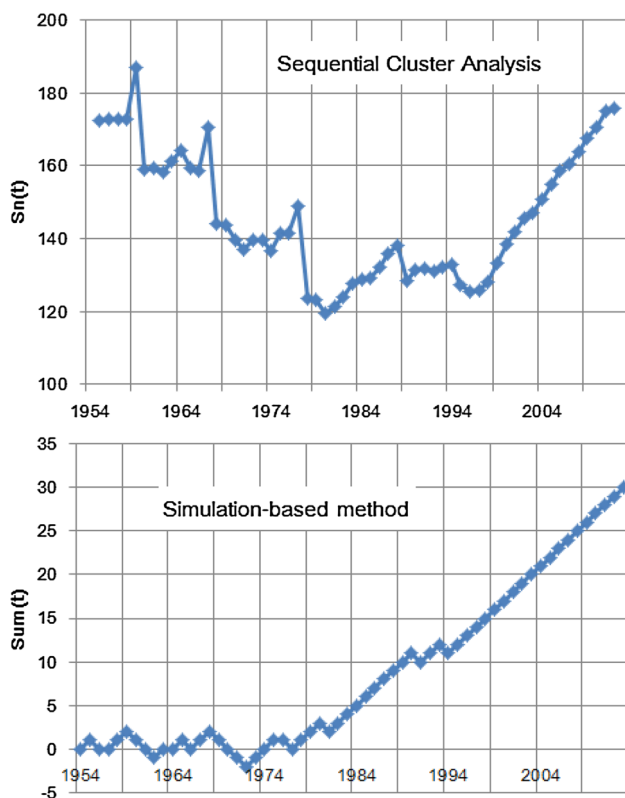

Fig. 5 Time series of Sn(t) and Sum(k) at the Gaoshiya hydrometric station over 1954–2013

Figure 6 illustrates that the recorded and the simulated discharges match well in general. Statistical results indicate that the SimHyd model performs well for monthly runoff simulation at the Gaoshiya station achieving a higher simulation accuracy with a NSE of 82 % and RE of −0.32 %.

The calibrated model is then driven by the meteorological data (i.e. monthly precipitation, pan evaporation.) for the entire period of record (1954–2013), using a constant set of calibrated parameters to generate runoff estimations. The simulated runoff reflects the benchmark situation without major human influences throughout the catchment. And time series Sum(t) is then constructed, representing the differences between the simulated and the recorded runoff (Fig. 5).

The time series of Sum(t) is depicted in Fig. 5. At the early stage, it varies around zero and departs from zero after 1977 with a consistent increasing trend due to human activities decreased stream flow, which means abrupt change in runoff series at the Gaoshiya station occurred in the late 1970s. The Local Statistical Year Book series document that water engineering projects as well as soil and water conservation measures have been implemented in the Gushan River catchment since the late 1970s (NBSC 2013), which is generally in accordance with the timing of changes we detected by two methods (i.e. Sequential cluster analysis and Simulation-based method). Comprehensively considering detection results and practice of human activities in the Gushan River catchment, 1954–1979 was then treated as a natural period, which was then taken as a baseline for investigating impacts of climate change and human activities on change in runoff in this study.

For the whole period of 1954–2013, the annual recorded and simulated runoffs are compared in Fig. 7. The figure suggests that the annual recorded and simulated runoffs before 1980 match well in general. However, most of the simulated runoffs in period of 1980–2013 are much higher than the recorded which explains the reduction in runoff induced by human activities to some extent. Statistical results indicate that the annual runoff and precipitation during 1980–2013 decrease by 14.2 and 62.8 % compared to 1954–1979, respectively, while temperature increase by 0.33 °C.

Attribution analysis of changes in runoff of the Gushan River catchment

Rainfall is a source of stream flow of the Gushan River catchment. Evaporation is another way in which water is removed from the hydrologic cycle in a catchment. Theoretically, a rise in temperature will result in an increase in potential evaporation, and accordingly, lead to a decrease

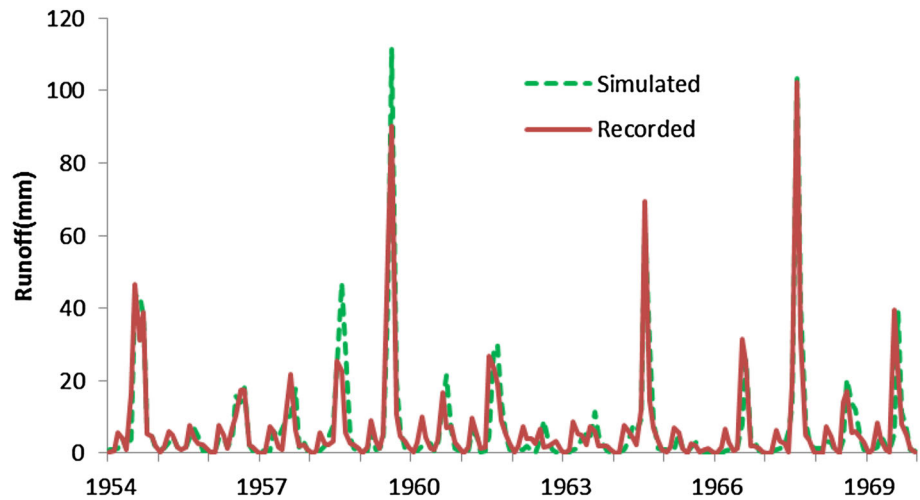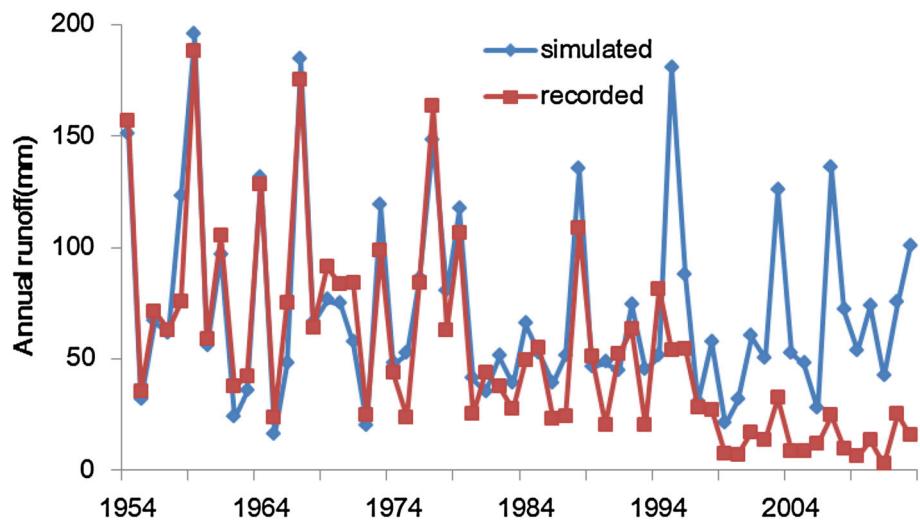**Fig. 6** Monthly recorded and simulated runoff at the Gaoshiya station over 1954–1965

Fig. 7 Annual recorded and simulated runoff at the Gaoshiya station over 1954–2013

in stream flow. Human activities, e.g. soil and water conservation measures, water consumption for agriculture and industry development, have direct influences on stream flow. For better understanding the potential drivers of changes in runoff with focus on periods before and after 2000, time series of the Gushan River catchment over 1954–2013 was divided into three phases of 1954–1979, 1980–1999, and 2000–2013, and annual discharges of the three phases have been plotted against areal precipitation and temperature and illustrated as in Fig. 8.

Figure 8 indicates that annual runoff is highly correlated to precipitation with linear correlation coefficients ranging from 0.513 to 0.726, which implies precipitation governs water resources. However, the points plotted for runoff against precipitation for the different phases fall into the different domains. For the same precipitation, runoff in natural period of 1954–1979 is much higher than the

second and third periods of 1980–1999 and 2000–2013, which means the relationship between runoff and precipitation has been changed by other drivers, e.g. human activities. Human activities induced a certain reduction in runoff. Although the points of runoff against temperatures are highly scattered, there exists decreasing trends of runoff with temperature rise for all three phases, showing discharges are weakly correlated to temperature (linear correlation coefficients ranging from 0.012 to 0.179) and implying temperature is but not a dominant driver of change in stream flow.

Taking the pre-1980 recorded runoff as the baseline, the effects of climate change (i.e. changes in precipitation and temperature) and human activities on runoff in the Gushan River catchment are analyzed through comparing baseline, naturalized and recorded runoff, and the results are presented in Table 2.
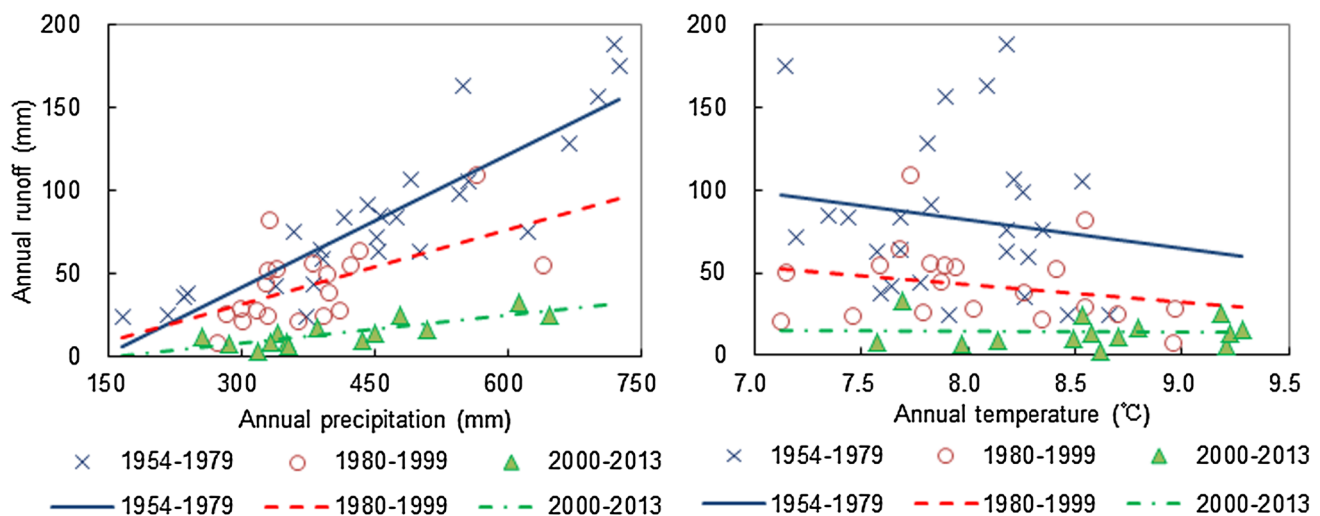
Fig. 8 Relationships of annual runoff against annual precipitation (*left*) and temperature (*right*)

Table 2 Impacts of climate change and human activities on runoff of the Gushan River catchment

Period	Recorded runoff (mm)	Simulated runoff (mm)	Total runoff reduction (mm)	Human-induced change		Climate-induced change	
				mm	%	mm	%
1954–1979	83.40	83.39					
1980–1999	42.80	59.99	40.60	17.18	42.32	23.42	57.68
2000–2013	14.18	67.82	69.23	53.64	77.49	15.58	22.51
1980–2013	31.02	63.21	52.39	32.20	61.46	20.19	38.54

From Table 2, four points can be concluded as follows. (1) The recorded runoff in the Gushan River catchment decreases from 83.4 mm in the baseline period to 42.8 mm in the second phase and 14.2 mm in the third phase. However, the naturalized runoff in the third phase (67.8 mm) is higher than that in the second phase (60.0 mm), and the both are much less than the baseline (83.4 mm in 1954–1979). (2) On average, annual recorded runoff over 1980–2013 decreases by 52.4 mm relative to baseline. However, the total runoff reduction increases from 40.6 mm in 1980–1999 to 69.2 mm in 2000–2013 due to the environmental changes. (3) The absolute runoff reduction induced by human activities increases from 17.2 mm in 1980–1999 to 53.6 mm in the third phase while climate-induced runoff reduction decreases from 23.4 mm in the second phase to 15.5 mm after 2000. (4) Human activities play a principal role in the runoff reduction of the Gushan River catchment during 1980–2013. The percentage of human-induced runoff reduction to total runoff reduction is approximate 61.5 %.

Human activities can come in many forms, such as land use change, agricultural and industrial development, urbanization, reforestation, etc. Different types of human

activities can have different influences (i.e., direct or indirect influence) on regional water resources. These impacts should be explored in future studies.

Conclusions

Human activities together with climate change led to great change in runoff simultaneously. The recorded runoff at the Gaoshiya station of the Gushan River presents a significant decreasing trend with a linear decline rate of −1.541 mm/year. Human-induced abrupt change on runoff series is detected occurring in 1980 with a physically based detection method. The proposed SimHyd rainfall runoff model performs well for the simulation of natural monthly runoff over 1954–1969, with Nash and Sutcliffe efficiency criterion (NSE) of 82.6 % and the relative error of volumetric fit (RE) of 0.32 %.

Variation of precipitation dominates the variability of runoff. However, human activities play a principal role in runoff reduction. Recorded runoff in 1980–1999 and 2000–2013 decreases by 48.7 and 83.0 % compared to that of the baseline (1954–1979). Human-induced runoff

reduction accounts for 61.5 % of the total runoff reduction over 1980–2013. The absolute human-induced runoff reduction presents increasing trend over the whole period. It is, therefore, essential to consider the impact of human activities in water resources management as well as ecological restoration on the Loess Plateau.

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