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Using hydrological simulation to detect human-disturbed epoch in runoff series

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ABSTRACT

Runoff in major rivers in China has been decreasing in recent decades, mainly due to climate change and human activity. River basin managers have a critical interest in detecting and diagnosing non-stationaries in runoff time series. Here we use a rainfall runoff model-based approach to identify the human-disturbed periods of the record. The method is applied to the Kuye River catchment, located in the Loess Plateau, China. The SimHyd model performs well for simulation of monthly natural discharges, and the method suggests that discernable human influence began in 1980. Anthropogenic effects were detectable several years earlier at the downstream stations than the upstream stations, consistent with pace and timing of soil and water conservation measures implemented across the Kuye River catchment.

Key words | human-disturbed epoch, hydrological simulation, Kuye River catchment, runoff series

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INTRODUCTION

Human activities, such as land cover change, urbanization, and water conservation projects can alter the hydrological cycle and result in significant changes in runoff (Zhang & Wang 2014). Runoff in most major rivers in China has decreased substantially in recent decades, likely due to climate change and intensive human activity (Wang *et al*. 2013). Wang *et al*. (2009) and Bao *et al*. (2012) both concluded that human activities play a principal role in runoff reduction for the Hai River basin located in north China. River basin managers have a critical interest in detecting and diagnosing non-stationaries in runoff time series, so as to provide information for water resource assessments and projections.

Numerous studies aiming to detect abrupt change in hydrological series have generally adopted one of two types of methodologies: (a) investigation-based approaches (MWR 2000; NBSC 2013); or (b) statistically-based approaches (Wang *et al*. 2001; Yang & Tian 2009; Zhang *et al*. 2012; Wang *et al*. 2013; Zhang *et al*. 2014). The first type of approach is based on extensive field investigations to collect socioeconomic data and water conservancy data, such as water allocation data and catchment treatments (e.g. the China Statistical Yearbooks series, NBSC 2013). These studies are costly and require considerable human resources. The statistically-based approach is generally more popular due to its relative simplicity and lower cost.

Currently, there are many statistically-based approaches available in the literature to diagnose abrupt change in time series. For example, Ding (1986) identified the transition point of flood series with the maximum T test and the Lee–Heghinan method (Hu *et al*. 2009), and discussed the weaknesses of each method. Both tests are used widely. Wang *et al*. (2001) analyzed the year of abrupt change in annual runoff series at the Baijiachuan station of the Wudinghe River catchment using the sequential cluster analysis method, and found that this change lagged 2 years behind the implementation of large-scale soil and water conservation practices across the catchment. Wang *et al*. (2009) investigated abrupt change of runoff series for the Chaobai River catchment using this method, and found the recorded runoff series deviated in 1979. The sequential Mann–Kendall test method is also commonly used to detect abrupt change in time series (Wang & Fu 1992; Yang & Tian 2009; Sun *et al*. 2010). For example, Yang & Tian (2009)

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analyzed abrupt changes in the runoff series for the Haihe River. Other commonly used methods include rescaled-range (R/S) analysis (Bassingthwaighte & Raymond 1994; Wang *et al.* 2002), the rank sum test (Pettitt 1979; Somnath & Glen 2005), the Brown–Forsythe test (Zhang *et al.* 2005; Weyhenmeyer 2009), and Bayesian methods (Lee & Heghinian 1977). Lei *et al.* (2007) compared and ranked the performance of abrupt change point testing methods, and found different methods may lead to different detection results even for the same data series, and additional analysis on the causes of the abrupt change is recommended.

One limitation of statistically-based change detection approaches is their inability to distinguish human activity from climate non-stationaries (e.g. runoff variability induced by changes in precipitation and/or temperature). Here, a hydrological simulation model-based approach is proposed as a useful tool for runoff disturbance detection, applying the technique to a catchment in north-central China.

DATA SET AND METHODS

Description of study area

The Kuye River catchment is situated between 109.5 °E–111.1 °E longitude and 38.2 °N–39.8 °N latitude on the Loess Plateau, originating in the Bading Gully in Inner Mongolia, and flowing eastward to join the Yellow River at Wenjiachuan. The catchment is located in the East Asian Monsoon climate zone, which is generally arid to semiarid. The drainage area of the catchment is approximately 8,645 km^2 with a main stream length of 242 km. The river system contains two major tributaries (the Wulanmulun River and the Boniuchuan River) in its upper reach and eight tributaries in the middle and lower reaches, with the sub-catchment area of each tributary larger than 100 km^2 (Figure 1).

The Kuye River catchment has been highly disturbed by intensive human activity since the 1980s. This disturbance is caused by soil and water conservation measures to combat runoff loss and soil erosion, including construction of large and small dams, reforestation, building terraced land, and planting grass on hill slopes. As of 2006, local authorities had constructed six primary dams on the main river, with a total storage capacity of 0.176 billion m^3, as well as 1192 check dams on tributaries. The soil and water conservation measures created 9,939 ha of terraced land, 5,039 ha of dam-land, 265,189 ha of reforested area, and 93,823 ha of planted grassland (Xu *et al.* 2009).

There are four hydrometric stations on the Kuye River; Wenjiachuan is the station at the outlet of the catchment. Runoff time series data were obtained from the Chinese Ministry of Water Resources Hydrology Bureau (Table 1). Meteorological data at 17 rainfall stations (Figure 1) with data from 1955 to 2008 were collected from the China

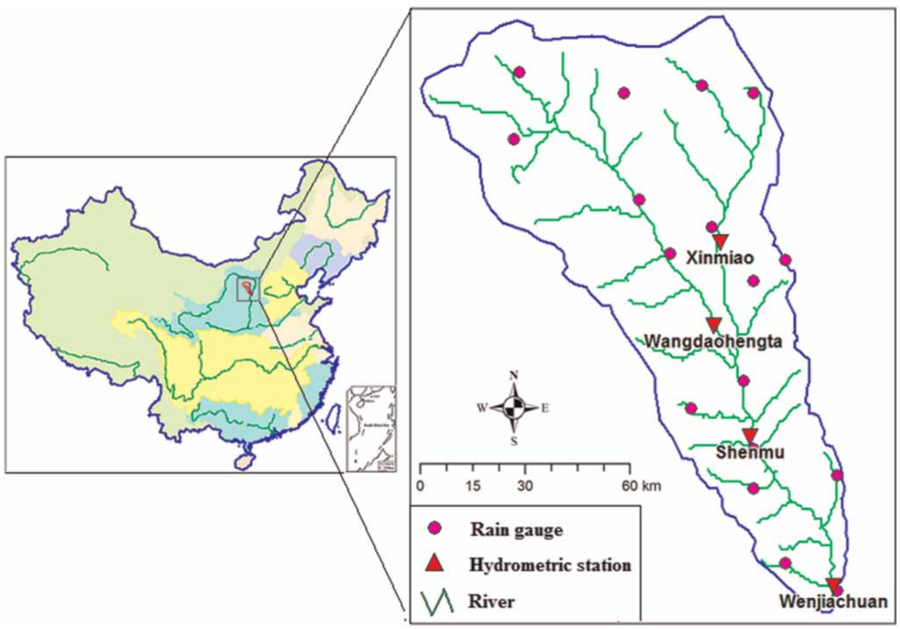

Figure 1 | River system and location of rain gauges and hydrometric stations in the Kuye River catchment.

Table 1 | Key hydrometric stations on the Kuye River used in the study

Station name	Locations		Period of data	Mean annual runoff (m^3/s)	Catchment area (km^2)
	Longitude	Latitude			
Wenjiachuan	110.75	38.48	1955–2008	16.89	8,515
Shenmu	110.50	38.80	1956–2004	14.74	7,298
Wangdaohengta	110.40	39.07	1959–2008	5.65	3,839
Xinmiao	110.37	39.35	1966–2008	2.75	1,527

Meteorology Administration as well as the Yellow River Conservancy Commission, and were used to calibrate the hydrological model.

Method for detection of change points in time series

In contrast to statistical change-detection methods, which can conflate anthropogenic and climate induced shifts, the hydrological model method examines simulated runoff with a consistent set of parameters and a time-varying climate. First, the hydrological model parameters are calibrated by minimizing the differences between simulated and observed runoff during a natural period; the calibrated model parameters reflect the situation prior to major human influences throughout the catchment. The model may perform well at simulating discharge, with low bias, during the natural period. Then consistent and persistent deviations between the simulated and observed time series during a different epoch suggest a change in the human influences during this period. The cumulative error of the runoff simulation will theoretically vary around zero for the natural period and will depart from zero after this change point, so the last point of the cumulative error curve close to the abscissa should be the human-induced change point of the time series. The detailed steps to detect the human-disturbed epoch are as follows.

(a) According to the variation of the recorded runoff series ($Q_{REi},\ i = 1, 2, \ldots, N$), initially determine a possible abrupt change point ($i = M$) before which runoff series maintain stationary variation with no significant trends, and preliminarily select a natural data series within the stationary series ($Q_{REi},\ i = 1, 2, \ldots, K,\quad K < M$) to calibrate and validate the hydrological model.

(b) According to the hydrological features and runoff yielding mechanism of study catchments, select a suitable hydrological model, and calibrate the model with the selected natural data series ($Q_{REi},\ i = 1, 2, \ldots, K, K < M$).

(c) Fix the original model parameters and use climatic variables for the whole period (such as rainfall and pan evaporation) to drive a rainfall runoff model to simulate runoff for the whole available data series ($Q_{SIMi},\ i = 1, 2, \ldots, N$).

(d) Construct a series to detect the abrupt change point CP, with the constructed series mathematically expressed as follows:

$$\mathrm{Sum}K_m = \sum_{i=1}^{m} K_i,\ (m = 1, 2, \ldots, N) \tag{1}$$

$$K_i = \begin{cases} +1 & Q_{SIMi} > Q_{REi} \\ 0 & Q_{SIMi} = Q_{REi} \\ -1 & Q_{SIMi} < Q_{REi} \end{cases} \tag{2}$$

The abrupt change point occurs at CP, after which $\mathrm{Sum}K_m$ will be continuously greater or less than zero. In the above equations, N is the length of observed runoff time series, Q_{SIMi} is the simulated runoff, Q_{REi} is the observed runoff, and K_i is the indicator of differences between the observed and simulated runoff in time step i.

Parameters of a conceptual hydrological model reflect, among other things, land cover, and texture of various soil types. If a catchment experiences large-scale land-use change, then its parameters would also need to change for the model to continue to simulate the observed runoff well. However, if the parameters are fixed to the natural state, then simulated runoff time series provides counterfactual information to the observed runoff during the altered period. The differences between simulated and observed runoff may give an indication of the extent of the human influence over the runoff.

Description of the SimHyd rainfall runoff model

The SimHyd model is a simplified conceptual rainfall runoff model that has been applied successfully in many semi-arid or semi-humid basins located in the United States, Australia, and other countries (Kachroo 1992; Chiew et al. 2002; Wang *et al*. 2006). Wang *et al*. (2006) compared the performance of five hydrological models, and found that the SimHyd rainfall runoff model performed well for monthly discharge simulation of arid catchments, and therefore it was selected for use in this study of the Kuye River catchment. The structure of the SimHyd model is shown in Figure 2.

Components of runoff simulated with the SimHyd model consist of surface flow, interflow, and base flow. The first component is an infiltration excess runoff, interflow is based on a saturation excess mechanism, and base flow is simulated as a linear recession function of groundwater store. Infiltration is a key component of this model and is simulated as a negative exponential function of soil wetness.

Interception of vegetation cover and evaporation from soil moisture storage are important losses of water within a catchment. The former is calculated by the potential evaporation rate, which is usually represented with pan evaporation rate, and the second part is estimated as a linear function of the soil wetness with an upper limit of atmospherically controlled potential evapotranspiration rate.

The SimHyd rainfall runoff model is a lumped hydrological model, which requires as input continuous data series of areal average precipitation and pan evaporation to estimate discharge series. Areal average precipitation and pan evaporation for each catchment were calculated using the method of Thiessen polygons.

We selected the Nash and Sutcliffe efficiency criterion (NSE) and the relative error of volumetric fit (RE) as objective functions to calibrate the model (Nash & Sutcliffe 1970). To evaluate model performance for low discharge simulation, NSEL (NSE of log discharge) was employed as the third objective function in this study (Zhang & Wang 2007, 2014). A good simulation result will give NSE, NSEL approaching 1 and RE approaching 0 (Wang *et al*. 2012).

RESULTS AND DISCUSSION

Variability of precipitation, temperature, and recorded runoff

Long-term variability of annual precipitation and temperature over the Kuye River catchment, and of annual runoff at four stations are shown in Figures 3 and 4. Figure 3 indicates that the annual precipitation varied from 140 to 650 mm, with higher variability before 1965. Although annual mean temperature fell in a relatively small range of 6.27–9.30 °C, it had a rising trend of 0.35 °C per decade for the whole period. The rise of annual temperature after 1985 was much faster than average, up to 0.81 °C per decade.

Figure 4 indicates that: (1) the annual runoff series are relatively stationary until approximately 1980 but overall runoff is decreasing, as indicated by the negative slope of the trend line (e.g. −0.96 mm/year at Shenmu); (2) most of the high-runoff years for the four stations occurred before 1980 and observed runoff has been continuously and unprecedentedly low since 2000; and (3) the human-disturbed epoch possibly started from 1980. Therefore, the period before 1980 was considered as the baseline and these 15 years were used to calibrate and validate the rainfall runoff model. The selected data series at the four hydrometric stations are Wangdaohengta station, 1959–1973; Xinmiao station, 1966–1980; Shenmu station, 1956–1970; Wenjiachuan station, 1955–1969.

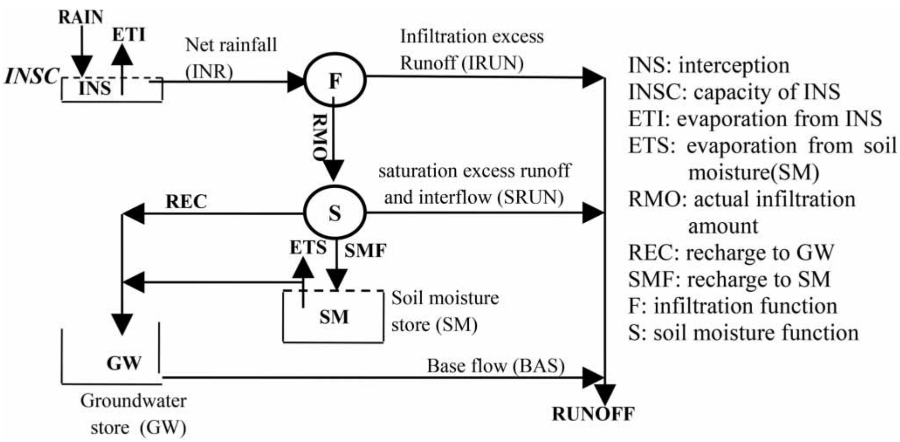

Figure 2 | Schematic diagram of the SimHyd rainfall runoff model.

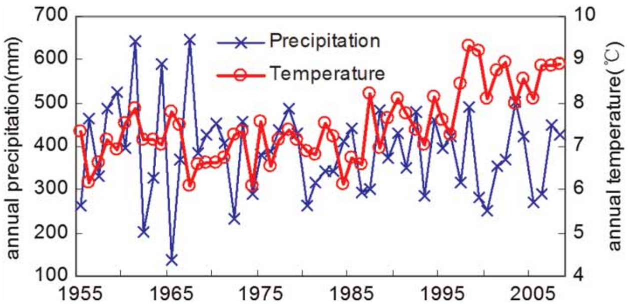

Figure 3 | Time series of annual precipitation and temperature over the Kuye River catchment.

Model calibration and verification

To evaluate the model's performance in discharge simulation, the data series was divided into two periods: the first 10 years was used as the calibration period and the latter 5 years was used as the verification period. The model was run at a daily time step and the results were aggregated to monthly discharge volumes at the hydrometric stations, using NSE, NSEL, and RE as objective functions to optimize model parameters. The monthly recorded and simulated discharges at the four stations are shown in Figure 5. Evaluations of the simulation results are summarized in Table 2.

Figure 5 shows that the recorded discharges at the four stations had very high variability with no significant trend. The simulated discharges generally matched well the recorded discharges for the four hydrometric stations, although peak monthly discharges were slightly oversimulated in most cases, namely at Wenjiachuan, Shenmu, and Wangdaohengta. The peak discharge at Xinmiao was slightly underestimated. The NSE criteria in calibration and verification were all above 70%, most of the NSEL criteria in both periods exceeded 70%, with the exception of Wangdaohengta station in the verification period, while the volume fit error RE over the long term were all <5% (Table 2). These results indicate that the SimHyd model can simulate both low flow and high flow well for all of the study sites. The model performed best for Shenmu station, where the NSE and NSEL criteria in calibration and verification were both above 75%.

Detection of the human-disturbed epoch

The calibrated SimHyd rainfall runoff model was forced by meteorological data for the entire period of record, using a constant set of parameters to generate runoff estimates (Figure 6). The simulated runoff reflects the benchmark situation without major human influences throughout the basin. The time series SumK_i was then constructed, representing the differences between simulated and recorded runoff at each of the four stations (Figure 6).

Figure 6 shows the following. (1) The simulated and recorded annual runoff at the four hydrometric stations match well, not only for the first 15 years (used for model calibration and verification), but also for several years after this period. This indicates that the first 15

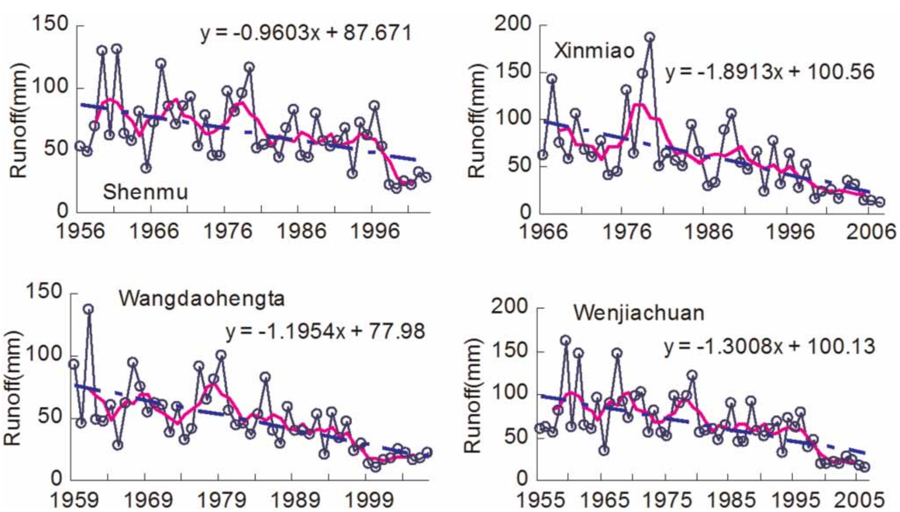

Figure 4 | Time series of annual runoff recorded (dotted line) at hydrometric stations in the Kuye River catchment and their 5-year moving average (red solid line) and linear trend line (light blue dashed line). The full colour version of this figure is available online at http://www.iwaponline.com/wst/toc.htm.

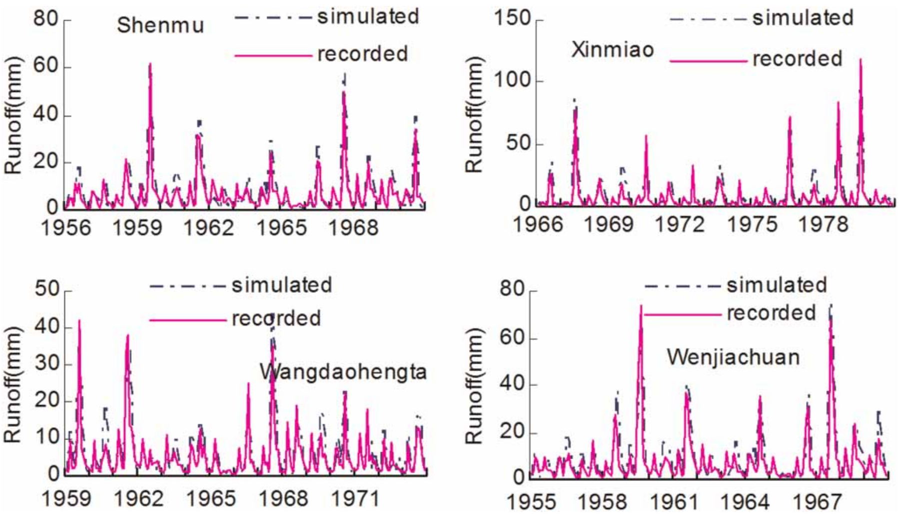

Figure 5 | Monthly recorded and simulated runoff at hydrometric stations in the Kuye River catchment.

Table 2 | Simulation results for monthly discharge at four key hydrometric stations of the Kuye River catchment

	Calibration period			Verification period		
Hydrometric station	**NSE (%)**	**NSEL (%)**	**RE (%)**	**NSE (%)**	**NSEL (%)**	**RE (%)**
Wenjiachuan	82.6	76.3	3.6	73.2	71.2	–2.4
Shenmu	78.6	75.6	–3.3	84.7	77.9	1.7
Wangdaohengta	76.8	72.5	–1.8	70.0	68.3	1.3
Xinmiao	72.4	72.4	0.4	80.7	74.1	2.1

years are in the natural period, but do not fully cover the natural period. (2) Because we keep model parameters constant, variability of the simulated runoff reflects the changes in climatic variables, such as the variability in precipitation and trends in temperature. In general, the simulated annual runoff tends to decline over the whole period, which could be attributed to natural (i.e. climatic) causes, particularly driven by the rise in temperature over recent decades. (3) The simulation errors (the difference between recorded and simulated runoff) become ever larger (overestimated) after 1980. This was especially true after 2000, when simulated runoffs were three to four times the recorded runoff, suggesting substantial human influence. Although Figure 6 indicates a clear trend of human-induced effects on runoff, it is still difficult to distinguish the starting year of abrupt change in the runoff series.

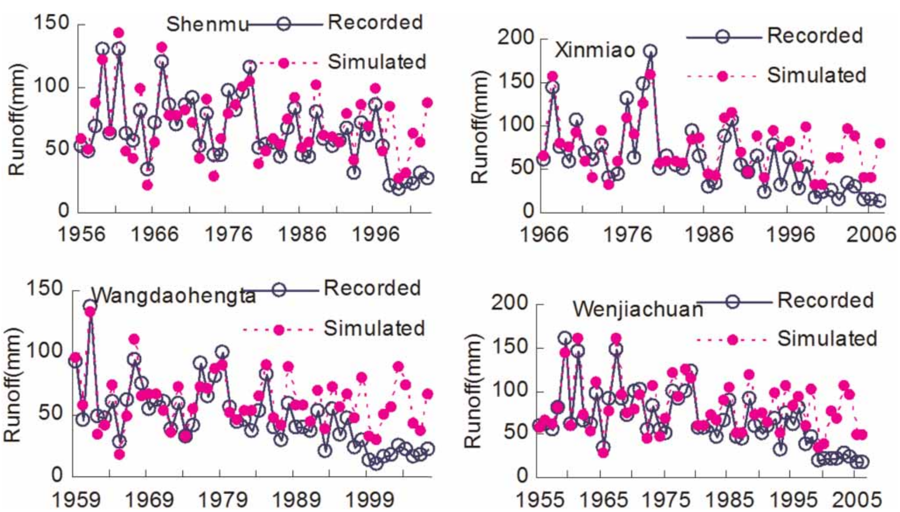

Figure 6 | Simulated and recorded annual runoff at hydrometric stations in the Kuye River catchment.

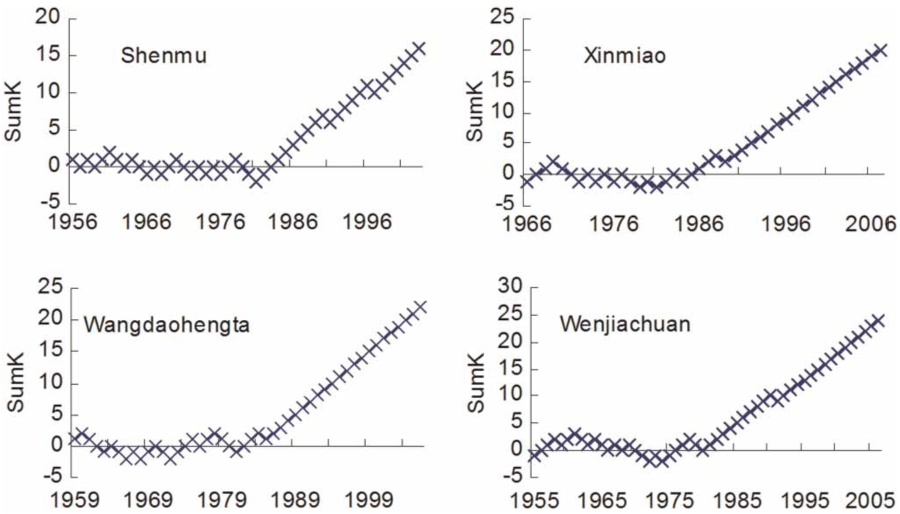

Figure 7 | Time series of Sum*K* at hydrometric stations in the Kuye River catchment.

Figure 7 shows that for all four stations, the time series SumK_i at first varies around zero, then departs from zero after a specific year, with a consistent trend. These figures clearly identify the human-disturbed epoch in the recorded runoff series at the four stations, with the years of abrupt change as 1982, 1985, 1983, and 1980 for Wangdaohengta, Xinmiao, Shenmu, and Wenjiachuan, respectively. It is noteworthy that at Wenjiachuan station, the most downstream station, the abrupt change in the runoff series occurred at least 2 years earlier than at upstream stations. The China Statistical Yearbook series document that, for economic reasons, water engineering projects (as well as other soil and water conservation measures) have been implemented from downstream to upstream (NBSC 2013), in accordance with the timing of changes we detected.

Results indicate that the average recorded runoff for the period of record after the abrupt change year decreased by 49.1%, 55.0%, 47.5% and 32.0%, respectively, as compared to that in the prior period for Wangdaohengta, Xinmiao, Wenjiachuan, and Shenmu. Changes of the seasonal flow distributions for four hydrometric stations were compared in Figure 8. Most monthly flows decreased by approximately 20–80%, with the exception of flows in June for Xinmiao and Shenmu stations. Flows in June at Xinmiao station and Shenmu station increased by 11.1% and 2.2%, respectively. Soil and water conservation measures within the Kuye River catchment have considerable effect on runoff for light and moderate precipitation conditions (normally less than 20 mm/d), but have very little effect on stream flow for heavy rain, particularly for extreme events

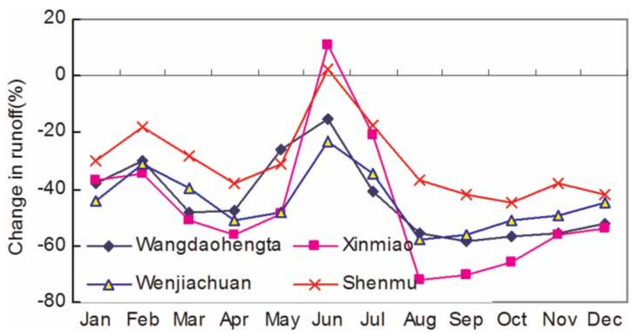

Figure 8 | Comparison of seasonal flow distributions before and after the change-points listed in the text.

(more than 50 mm/d) (Xu *et al.* 2009). In the East Asian Monsoon climate zone, the seasonal distribution of precipitation over the Loess Plateau is extremely uneven. More than 70% of annual precipitation concentrates in the flood season from June to August (Zhang & Wang 2007). Increases of flows in June may probably be induced by changes in extreme rainstorms during this month.

SUMMARY AND CONCLUSIONS

Hydrology in many catchments has been gradually disturbed by intensive human activities, and this can be evidenced by runoff time series with consistent trends. However, it is difficult to distinguish climate-driven trends from anthropogenic changes. Here, we have proposed and tested a new approach based on hydrological simulations to detect the human-disturbed epoch in runoff series. In contrast statistically-based approaches, this method not only considered the variation in runoff series itself, but also took into account the contribution of climate change.

The SimHyd rainfall runoff model was used to simulate natural runoff for the whole period, using parameters calibrated to data during the unaffected period only. The model performs well in monthly discharge simulation for both the calibration period and verification period, indicating that the naturalized runoff in the latter period is realistic.

The detectable human-disturbed epoch in the Kuye River catchment started in 1980. An abrupt change in runoff series induced by human activities occurred in 1980 at the Wenjiachuan station, the most downstream station, and 2–5 years later at upstream stations such as Xinmiao station and Wangdaohengta station, consistent with the patterns of development in this region.

The proposed simulation-based approach is effective and feasible in identifying the human-disturbed epoch in a runoff series. As the SimHyd model not only performs well for arid catchments, having successful experience in application to humid catchments (Chen *et al*. 2006), this approach thereby has potential to be applied to other regions. However, a shortcoming of this approach is the requirement for a long time series of data (which are unavailable in ungauged catchments), and the availability of data during the natural period (unaffected by human activity) to calibrate the model.

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