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Effect of climate changes and water-related human activities on annual stream flows of the Shiyang river basin in arid north-west China

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Abstract:

The change of annual stream flow in the Shiyang river basin, a typical arid-inland basin in north-west China, was investigated using hydrological, meteorological and water-related human activities' data of the past 50 years. The long-term trends of the hydrological time series were examined by non-parametric techniques, including the Pettitt and Mann–Kendall tests. Double cumulative curves and multi-regression methods were used to separate and quantify the effects of climate changes and human activities on the stream flows. The results show that the study area has been experiencing a significant upward warming trend since 1986 and precipitation shows a decreasing trend in the mountainous region but an increasing trend in the plains region. All stream flows in the upper reach and lower reaches of the Shiyang river exhibit decreasing tendencies. Since 1970, human activities, such as irrigation, have had a significant effect on the upstream flow, and account for 60% of total flow decreases in the 1970s. However, climate changes are the main reason for the observed flow decreases in the 1980s and 1990s, with contributions to total flow decrease of 68% and 63%, respectively. Before 1975, flow decreases in the upper reaches were the main factor causing reduced flows in the lower reaches of the Shiyang river. After 1975, the effect of human activities became more pronounced, with contributions of 63%, 68% and 56% to total flow decreases in the lower reaches of the Shiyang river in the periods 1975 to 1980, 1980s and 1990s, respectively. As a result, climate change is responsible for a large proportion of the flow decreases in the upstream section of the catchment during the 1980s and 1990s, while human activities have caused flow decreases downstream during the same period. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS climate changes; water-related human activities; stream flow; arid region; response of hydrological process

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INTRODUCTION

Limited water resources in arid regions are often the main factor restricting local economic development. It has been widely recognized that global climate changes, mainly global temperature increases and altered precipitation patterns, could have a significant impact on the regional hydrological cycles and subsequent changes in stream flow regimes (Govinda, 1995; McCabe and Hay, 1995; Niemann and Eltahir, 2005; Chen *et al.*, 2006;). Increased temperature is expected to cause a rise in potential evaporation losses, and less snow and alteration of precipitation directly cause changes to river runoff. In general, the drier the climate, the greater the hydrological sensitivity to climate change (Chen *et al.*, 2006).

Chen *et al.* (1991) analysed the changes of mean temperature in north-west China and concluded that this region may be one of the most sensitive to global warming. Lai and Ye (1995) investigated runoff time series at mountain outlets from 1955 to 1985 in north-west China and found positive anomalies were dominant before 1973, with negative anomalies dominant after 1973. Much research focused on climate and runoff changes for individual basins in arid regions has been conducted recently (Chen *et al.*, 2006; Kader and Hiroshi, 2006; Li *et al.*, 2006; Zheng *et al.*, 2006) and show that over the past 50 years, climate changes have influenced river discharges. According to Shi and Zhang (1995), from analysing the relationship among different climate factor trends, they concluded that the mean temperature in the mountainous regions of north-west China will be 1 °C warmer by 2030, making precipitation and evaporation higher, thus altering annual river discharges.

Due to the growth in population, the development of industry and agriculture, and urban construction, such as irrigation and drainage, and hydraulic structures, the elements of the hydrological cycle have changed in terms of quantity and quality, both in time and space (Bhowmik, 1987; Szilagyi, 2001; Geng, *et al.*, 2002; Ren *et al.*, 2002; Wilk and Hughes, 2002; Ye, 2003; Levashova *et al.*, 2004;). Hydrological systems in arid regions are more sensitive to human activities, and many river flows in these regions have been changed in the past 50 years. In arid central Asia, the annual inflows into Lake Balkhash from the River Ili after 1970 decreased to 77% of the pre-1969 mean (Kader and Hiroshi, 2006). Analysing changes of long-term runoff in a northern area of China, Ren *et al.* (2002) found that annual runoff generated from the same order of precipitation in the

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1980s and 1990s decreased by 20–50%, compared to the 1950s and 1960s. At the same time, they concluded that the impact of human activity (e.g. changes in land use, construction of new reservoirs, etc.) on stream flows is stronger in arid or semi-arid areas than in humid areas. Wang *et al*. (2006) investigated stream flow of the Heihe river basin in north-west China and showed that the downstream flow has declined by 27·32% due to the continuous expansion of the cultivated land area, which contributed 14–31% of total annual flow decrease. The remaining decreases in flow are attributed to climate change and other human activities. Consequently, it is necessary to investigate the response of hydrologic systems to a combination of climate changes and human activities in arid regions.

Traditionally, the arid north-west China is confined to the arid inland north of 35°N and west of 106°E, and includes all of Xingjiang Autonomous Region, the Hexi Corridor in Gansu Province, and the area west of the Helan Mt. in the Inner Mongolia Autonomous Region (Shi and Zhang, 1995). In these regions, the mean annual precipitation is only 160 mm and the annual runoff volume is 946×10^8 m^3, just 3·34% of the quantity for the entire country, although the area accounts for about 24·5% of China (Ministry of Water Resources PR China, 1987). It is well known that the ecological environment in north-west China is vulnerable to water shortages. The conflict between ecological protection and economic development has become more prevalent as a result of increased utilization of water resources, and the sustainable development of the regional economy is severely constrained by water shortages.

Unfortunately, climate change and human activities have induced negative changes in hydrological systems in arid north-west China. From the 1950s to the 1990s, the annual runoff from the Tarim river in the Xingjiang Uygur Autonomous Region decreased by 21·1%, 40·6% and 79·9%, respectively, in the upper, middle and lower reaches (Geng *et al*., 2002). The annual runoff from the Hei river in the Hexi corridor decreased from $12{\cdot}06 \times 10^8$ m^3 year^{-1} in the 1950s to $7{\cdot}56 \times 10^8$ m^3 year^{-1} in the 1990s (Liu *et al*., 2005). With the economic development of north-west China, some negative effects, such as deforestation, desertification, and soil salinity have also been considerable (Ji *et al*., 2006). In particular, downstream water curtailment has had a major adverse impact on the ecosystems in the Tarim River basin in Xingjiang Uygur Autonomous Region, the Hei River basin, and Shiyang River basin in the Hexi corridor (Wang and Cheng, 1999; Wang *et al*., 2002; Kang *et al*., 2004; Chen *et al*., 2006). Because of these adverse impacts, it is important to investigate hydrological processes to better understand the causes of water resources scarcity, so that a new vision for future water management in these arid regions may be formulated. Although there is some research focused on the effects of climate changes and human activities on stream flow in arid regions, none have attempted to rigorously separate and quantify the impacts of climate changes and human activities on stream flow.

For this study, the Shiyang river basin in the Hexi corridor of China, a typical river in arid north-west China, was selected as the study area. Climate, hydrological, and irrigation area data over the past 50 years were used to evaluate the long-term trend in temperature and precipitation time series and the sensitivity of stream flows to climate changes and human activities, such as land use changes, irrigation, and groundwater extractions in the basin. Stream flows without high human activities impact were reconstructed to separate and quantify the magnitude of the flow decrease due to the influence of climate changes and human activities.

MATERIALS AND METHODS

Study area

The Shiyang River basin, one of three continental rivers in the Hexi corridor, is located in the eastern portion of the corridor in Gansu province of north-west china. The basin encompasses an area of $4{\cdot}16 \times 10^4$ km^2 with a population of 2·2 million and covers the area between 101°41′–104°16′E and 36°29′–39°27′N (Figure 1). The Shiyang river basin includes three climate zones (Kang *et al*., 2004). The Qilian Mountain in the south of the basin comprises a very frigid, semiarid-humid area. The middle part of the basin is the Wuwei sub-basin, cool and arid. The northern part of the basin, also called the Minqin sub-basin, is warmer and more arid. The detailed climate data for these three zones are given in Table I.

The Shiyang River starts from north of the Qilian Mountains and includes eight tributaries, but only five tributaries, the Zamu, Gulang, Huangyang, Jinta and Xiying, converge as the Shiyang River in the outlet of the Qilian Mountains, and then flow into the Hongyashan reservoir in the Minqin oasis, the largest desert reservoir in Asia (Figure 1). The five tributaries are mainly fed

Table I. The elevation, annual average temperature, total precipitation, total potential evaporation and DI scope of three zones in the Shiyang River basin

	Elevation (m)	Temperature (°C)	Precipitation (mm)	Evaporation (mm)	DI
Qilian mountain	2000–5000	−0·1	300–600	700–1200	1–4
Wuwei basin	1500–2000	7·5	150–300	1200–2000	4–15
Minqin basin	1300–1500	8·1	100–150	2000–2600	15–25

Note: DI-the ratio of potential evaporation to precipitation.

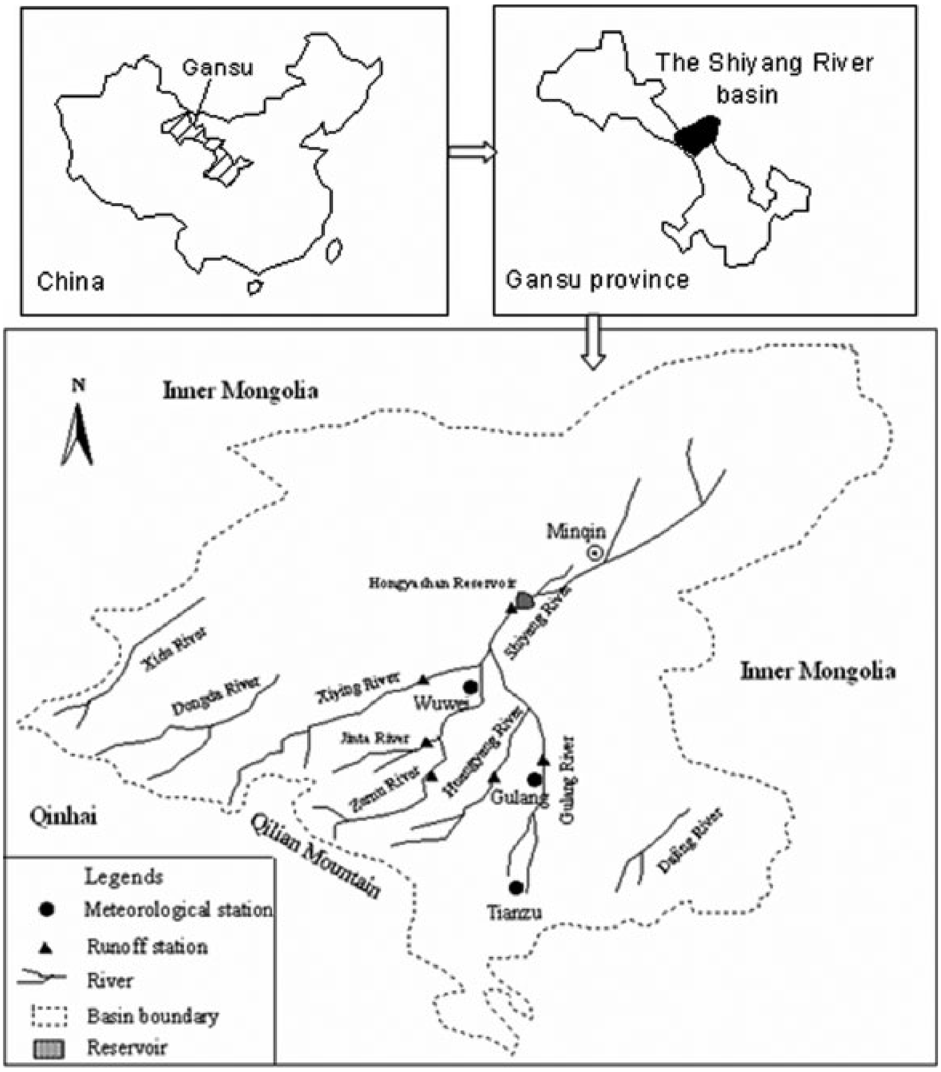

Figure 1. Location of the Shiyang River in China and its sketch map

by rainfall, snowmelt, and glacier melt from the Qilian Mountain. In the Wuwei sub-basin, there are some spring flows into the Shiyang River. The annual average natural surface flow of the five rivers is about $9{\cdot}62 \times 10^8$ m^3 at mountain outlets, and the average inflow into the reservoir is only $2{\cdot}85 \times 10^8$ m^3 over the last five decades. In summary, all streamflows have steadily decreased, particularly the inflow into the Hongyshan reservoir, as climate changes and water-related human activities such as irrigation and groundwater extraction have increased in recent years.

Data collection

As the climate differences are significant over space within the Shiyang River basin, we collected annual mean daily temperature and annual precipitation data from 1950 to 2002 from three meteorological stations (i.e. Tianzu, Gulang, Wuwei) along the Shiyang River (Figure 1). To analyse the long-term trend, stream flow time-series from 1950 to 2003 for five tributaries and inflow into the Hongyashan reservoir were used. The stream flow data for the five tributaries is from observation stations at mountain outlets. Flow data for the Shiyang River were measured at the hydrological station located at the inlet of the Hongyashan reservoir (i.e. inflows into the Hongyashan reservoir) (Figure 1). In addition, to analyse the impact of human activities on the runoff of Shiyang River flows, other data including irrigation area, spring flow, groundwater exploitation, and diverted surface water for the past five decades in the Wuwei sub-basin were obtained from the Wuwei Department of Water Resources for analysis. Spring flows are from several typical springs in different regions, and were summed to give total spring flow. The diverted surface water is the actual measured value, while groundwater extraction was estimated on the basis of irrigation area, irrigation volume, and diverted surface water volume.

Mann–Kendall test. Hypothesis testing for long-term trends of climate changes and stream flows can help discern the inherent mechanisms of a hydrological process. In this study, we used the non-parametric Mann–Kendall test (Chen *et al.*, 2006) to investigate possible trends in temperature, precipitation, and stream flows. In the Mann–Kendall test, there is the null hypothesis H_0 that

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the data (X_1, X_2, $X_3 \ldots X_n$) is a sample of n independent and identically distributed random variables. The alternative hypothesis H_0 of a two-sided test is that the distributions of X_k and X_j are not identical for all k, j. The Mann–Kendall's statistic S is given by

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

where the time-series x_i is from $i = 1, 2, \ldots, n-1$, and x_j from $j = i+1, \ldots, n$.

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

Then, the parameters Z_c and β are given as

$$Z_c = \begin{cases} \dfrac{S-1}{\sqrt{\operatorname{var}(S)}} & S > 0 \\ 0 & S = 0 \\ \dfrac{S+1}{\sqrt{\operatorname{var}(S)}} & S < 0 \end{cases} \tag{3}$$

where Z_c is the test statistic. When $|Z_c| > Z_{1-\alpha/2}$, in which $Z_{1-\alpha/2}$ are the standard normal deviates and α is the significance level for the test, H_0 will be rejected. The magnitude of the trend is given as

$$\beta = \text{Median}\left(\frac{x_i - x_j}{i - j}\right), \ \forall j < i \tag{4}$$

where $1 < j < i < n$. A positive value of β indicates an 'upward trend', whereas a negative value of β indicates a 'downward trend'.

Analyses on long-term climate series indicate that abrupt climate changes occurred in north-west China around 1975 (Chen *et al.*, 1991). In arid or semi-arid regions, relatively small changes in precipitation and temperature may result in significant changes in runoff (Gan, 2000). Consequently, in this study, the climate and stream flow time-series are divided into two periods, pre-1975 and post-1975, to investigate the change trends.

Change-point analysis

The non-parametric approach developed by Pettitt (1979) was used in this study. This approach detects a significant change in the mean of a time series when the exact time of the change is unknown. The test uses a version of the Mann–Whitney statistic $U_{t,N}$, which verifies whether two sample $x_1, \ldots\ldots, x_t$ and $x_{t+1}, \ldots\ldots, x_N$ are from the same population or not. The test statistic $U_{t,N}$ is given by

$$U_{t,N} = U_{t-1,N} + \sum_{j=1}^{N} \operatorname{sgn}(x_t - x_j) \quad \text{for } t = 2, \ldots\ldots, N \tag{5}$$

The test statistic counts the number of times a member of the first sample exceeds a member of the second sample. The null hypothesis of Pettitt's test is the absence of a changing point. Its statistic $k(t)$ and the associated probabilities used in significance testing are given as

$$k(t) = Max_{1 \le t \ge N} |U_{t,N}| \tag{6}$$

and

$$p \cong 2\exp\{-6(K_N)^2/(N^3 + N^2)\} \tag{7}$$

Double cumulative curves

This method was applied to determine the time when human activities began to obviously influence upstream and/or downstream flows. The double cumulative curve between precipitation and total flow for the five tributaries (i.e. at mountain outlets) and the double cumulative curve between the five flows at mountain outlets and inflow into the Hongyashan reservoir were used to detect, respectively, the effects of human activities on upstream and downstream flows. The double cumulative curves can be defined by

$$Y(t) = F(X(t)) \tag{8}$$

For the double cumulative curve between precipitation and total flow of five tributaries at mountain outlets,

$$X(t) = \sum_{i=1}^{t} P_{ui},\ Y(t) = \sum_{i=1}^{t} W_{ui} \tag{9}$$

while for the double cumulative curve between the five river flows at mountain outlets and inflow into the Hongyashan reservoir,

$$X(t) = \sum_{i=1}^{t} W_{ui},\ \ Y(t) = \sum_{i=1}^{t} W_{di} \tag{10}$$

where P_{ui} (mm) is the annual precipitation in the mountain region for year i, and is calculated using annual average precipitation in Tianzu and Gulang stations. W_{ui} (10^8 m^3 year^{-1}) and W_{di} (10^8 m^3 year^{-1}) represent the total flow of the five tributaries and the flow of Shiyang river flow for year i, respectively. For the investigation of upstream flow, $Y(t)$ (mm) and $X(t)$ (10^8 m^3 year^{-1}) represent the cumulative precipitation in the mountainous region and the total flow of five tributaries for year t, respectively. For the investigation of downstream flow, $Y(t)$ (10^8 m^3 year^{-1}) and $X(t)$ (10^8 m^3 year^{-1}) are cumulative total flow of the five tributaries and the cumulative flow of the Shiyang rive for year t, respectively.

When influenced by only natural factors, the double cumulative will be a straight line. The inflection of the curve denotes when human activities began to significantly influence downstream flow in the corresponding year. The cumulative decreased flow by human activities can be computed using the following equation.

$$\Delta W_t = Y'(t) - Y(t) \tag{11}$$

where $Y'(t)$ (10^8 m^3 year^{-1}) is the estimated cumulative flow in year t, extrapolated by a straightline regression from flow under the approximate natural condition.

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For this case, ΔW_t (10^8 m^3 year^{-1}) is the cumulative decreased flow by human activities in year t.

Reconstruction of stream flows

To better understand and quantify the effect of human activities on annual upstream and downstream characteristics, reconstruction (naturalization) of stream flow records is necessary. Various methods, including a physical based hydrological model, have been developed for reconstructing stream flow data in regulated watersheds. In this study, the limited information and data sets available fail to satisfy the minimal requirements for developing physical-based stream flow models. Consequently, statistical methods were used to determine the relationships between climate changes/natural conditions and streams flows, and these relationships were applied to reconstruct upstream and downstream flow data. In order to reconstruct the flow as nearly as possible as it actually occurred, auto-regression (AR) and multi-regression (MR) methods were selected to simulate flow change in the absence of human activities. Based upon a comparison between results obtained with the two methods, one can determine which statistical method is most effective (accurate?) for reconstructing historical flows.

(1) A*uto-regression*
This method can be mathematically represented as

$$X_t = \phi_{p,0} + \phi_{p,1}X_{t-1} + \phi_{p,2}X_{t-2} + \cdots + \phi_{p,p}X_{t-p} + \varepsilon_t \quad (12)$$

in which

$$\phi_{p,0} = (1 - \phi_{p,0} - \phi_{p,0} - \cdots - \phi_{p,p}) \cdot \overline{X} \quad (13)$$

whereby $\overline{X}$ is the average value of upstream flow and downstream flow, $\phi_{p,0}, \phi_{p,1}, \phi_{p,2}, \cdots, \phi_{p,p}$ are auto regression coefficients, and ε_t is a coefficient denoting a random term. The detailed procedure for determining these coefficients can be found in Robert and Linda (2000).

(2) M*uti-regression*
This method can be mathematically represented as

$$W_{ru} = \gamma_0 + \gamma_1 P_u + \gamma_2 T_u \quad (14)$$

$$W_{rd} = \lambda_0 + \lambda_1 P_d + \lambda_2 T_d + \lambda_3 W_{ou} \quad (15)$$

where W_{ru} and W_{rd} (10^8 m^3) are the reconstructed annual upstream (total flow of five tributaries at outlets of mountains) and downstream flows (inflow into the Hongyashan reservoir), respectively. The variables P_u (mm) and T_u (°C) denote annual precipitation and mean temperature within the upper reaches of the Shiyang river basin, and in this study, they are the mean values of precipitation and temperature measured at the Tianzu and Gulang stations, respectively. The variables P_d (mm) and T_d (°C) are precipitation and mean temperature measured in the middle reach of the Shiyang river basin, obtained from the Wuwei station. The variable W_{ou} (10^8 m^3) is the annual observed upstream flow, which is the sum of the flows in the five tributaries. The constants γ_0, γ_1, γ_2 and λ_0, λ_1, λ_2, λ_3 are the regression coefficients, respectively for reconstructed upstream flow and downstream flow models, and are obtained using the least-squares method.

The annual stream flow change of upstream and downstream flows induced by human activities can be calculated using the following equation,

$$\Delta W_u = W_{ru} - W_{ou},\ \Delta W_d = W_{rd} - W_{od} \quad (16)$$

where ΔW_u and ΔW_d (10^8 m^3) are annual stream flow changes induced by human activities, respectively, upstream and downstream on the Shiyang river. Accordingly, the extent of stream flow response to human activities and the degree of contribution of human activities on stream flow decreases can be defined as

$$R_u(\%) = \frac{\Delta W_u}{W_{ru}} \times 100,\ R_d(\%) = \frac{\Delta W_d}{W_{rd}} \times 100 \quad (17)$$

$$C_u(\%) = \frac{\Delta W_u}{W_{u50} - W_{ou}} \times 100,\ C_d(\%) = \frac{\Delta W_d}{W_{d50} - W_{od}} \times 100 \quad (18)$$

where R_u and R_d are the extents of upstream and downstream flow responses to human activities respectively, and C_u and C_d are the degree of contribution of human activities to upstream and downstream flow decreases, respectively. W_{u50} and W_{d50} are the initial annual stream flow of the upstream and downstream segments at the start of the study period. In this study, the mean flow quantities at mountain outlets ($12{\cdot}07 \times 10^8$ m^3) and inflow into the Hongyashan reservoir ($5{\cdot}36 \times 10^8$ m^3) were calculated for the 1950s to represent W_{u50} and W_{d50}, respectively.

RESULTS AND DISCUSSION

Trends of temperature and precipitation

Because the long-term trend in hydrological processes is potentially affected by climate change, and because natural variability is considered to be an important factor for variation in stream flow (Shi *et al.*, 1995), examining the historical trend of these of variables may help to reveal the effect of climate change on water resources systems (Chen *et al.*, 2006). The annual temperature and precipitation data from three stations measured over the last 50 years were analysed using non-parametric Mann–Kendall and Pettitt tests to identify long-term trends. The results of the non-parametric Mann–Kendall test for monotonic trends and the Pettitt test for change

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Table II. Results of trend analysis for annual mean temperature and precipitation in the selected three stations in the Shiyang river basin[a]

		Pettitt	Mann–Kendall					
		Change year	First stage			Second stage		
			Z_c	β	H_0	Z_c	β	H_0
Temperature	Tianzu	1986	−1·936	−0·045	R	3·666	0·035	R
	Gulang	1986	−1·731	−0·014	A	3·571	0·066	R
	Wuwei	1986	−1·121	−0·053	A	2·856	0·063	R
Precipitation	Tianzu	1986	−2·263	−8·563	R	−0·795	−3·356	A
	Gulang	1986	−1·391	−2·351	A	−1·213	−3·055	A
	Wuwei	1986	1·171	2·578	A	1·500	0·817	A

[a] First stage is from 1950 to the change year; second stage is from the change year to 2001. Z_c and β are test statistics. H_0 is the hypothesis that the data is a sample of n independent and identically distributed random variables. R: rejected; A: accepted; Significance level $\alpha = 0{\cdot}05$.

points for both temperature and precipitation time series are given in Table II.

It can be observed from the Pettitt test results that all annual temperature series for all three stations have a change point in 1986. From 1950 to 1986, there is a gradual, decreasing temperature trend, but the results of the Mann–Kendall test show that the decrease is not significant at the 5% level, except for the Tianzu station. After 1986, temperature exhibits an increasing trend of approximately 0·04 °C, 0·07 °C, and 0·06 °C year^{-1}, respectively, for the Tianzu, Gulang and Wuwei stations, at the 5% level of significance (where the Mann–Kendall test rejects the H_0). The Mann–Kendall slope, β, departs from zero for all three stations, indicating a trend for monotonic increase. However, the amplitude of the temperature change is relatively small for nearby high mountains (Tianzu), where there are sufficient water resources to offset temperature changes.

As with temperature, the precipitation series have a change point in 1986 also. It is apparent that the trends in annual precipitation among the three stations are different, even though all precipitation time-series have a monotonic tendency over the last 50 years. In Tianzu and Gulang, which are near to the Qilian Mountain, annual precipitation trends exhibit declines of about 8·6 mm year^{-1} and 3·4 mm year^{-1} (for Tianzu) and 2·4 mm year^{-1} and 3·1 mm year^{-1} (for Gulang), respectively, for pre-1986 and post-1986. Based upon the Mann–Kendall test, these decreasing trends are not significant at the 5% level except in Tianzu from 1951 to 1986. However, annual precipitation in Wuwei, which is located within the plain of the middle reach of the Shiyang river basin, has an increasing trend of about 2·6 mm year^{-1} and 0·8 mm year^{-1}, respectively, for the two periods, although the trend is not significant at the 5% level (Table II). Overall, there are decreasing trends in the mountain region, which is more obvious in regions with the highest altitude, but increasing trends in the plain region.

Water-related human activities

With the continuous increase of population and the developments of industry and agriculture, the effects of water-related human activities, especially agricultural production activities, on hydrology have been intensified in recent years. In the Shiyang river basin, water-related human activities mainly refer to extracting both surface water and groundwater to satisfy the continuous expansion of irrigated agricultural land. The irrigation area has increased from 25·2 kha in 1950 to 101·2 kha in 2002, increasing since 1970 at an average rate of 0·97 kha per year, which increased total water diversions from the Shiyang River. Diverted surface water increased from about $4{\cdot}0 \times 10^8$ m^3 per year before the 1970s to about $6{\cdot}0 \times 10^8$ m^3 per year after the 1970s, even exceeding $7{\cdot}0 \times 10^8$ m^3 per year, which represents approximately 80% of the total annual discharge of the Shiyang river during the 1990s in the Wuwei sub-basin. The increased lining of canals has reduced the recharge of surface water to groundwater, and induced a decline in groundwater levels.

Beginning in the 1970s, higher groundwater volumes were also exploited for irrigation, resulting in groundwater levels declining at an alarming rate of 0·3–1·2 m year^{-1}. In addition, to enhance the irrigation water use efficiency, canals were lined to reduce water loss via bottom infiltration. Presently, 81% of the main canals, 75% of the secondary canals, and 75% of branch canals have been lined (Kang *et al*., 2004). This lining reduces groundwater recharge, which accelerates groundwater level declines. Generally, the spring overflow quantity is sensitive to the declining regional groundwater table. Research has shown that overexploitation of 1×10^8 m^3 groundwater can result in a spring overflow decrease of $0{\cdot}78 \times 10^8$ m^3 (Ding *et al*., 2003). With the increase of groundwater exploitation, the total spring overflow quantity in the Wuwei sub-basin decreased by about 75%, from $3{\cdot}92 \times 10^8$ m^3 in 1969 to $1{\cdot}04 \times 10^8$ m^3 in 1999 (Figure 2).

Stream flow changes

Long-term climate changes and human activities can alter the pattern of stream flows, as well as the timing and frequencies of hydrological events, particularly in arid and semi-arid regions (Gan, 2000). Consequently, because of concerns regarding the delicate ecosystem,

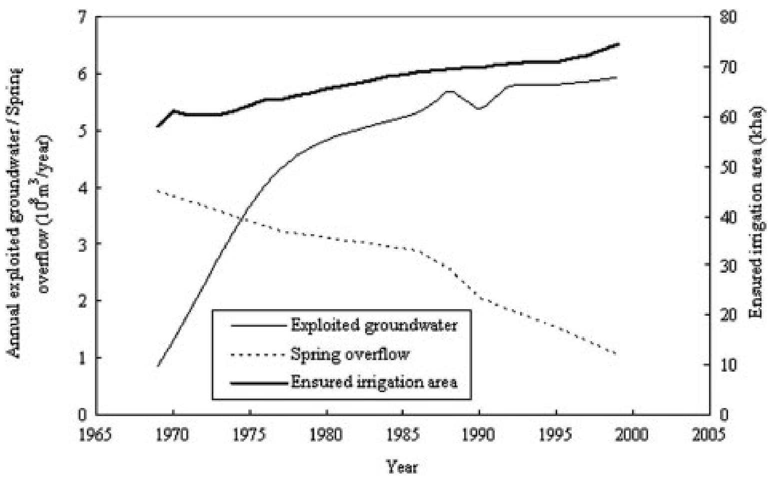

Figure 2. Irrigation area, exploited groundwater and spring overflow changes in the Wuwei sub-basin since 1970

Table III. Results of trend analysis for annual flows in the five tributaries, total flows and the inflow into the Hongyashan reservoir[a]

	Pettitt Change year	Mann–Kendall					
		First stage			Second stage		
		Z_c	β	H_0	Z_c	β	H_0
Xiying	1961	−2·425	−0·013	R	−1·517	−0·040	A
Jingta	1961	−2·174	−0·022	R	−2·361	−0·024	A
Zamu	1961	−3·262	−0·025	R	−0·057	−0·014	A
Huangyang	1964	−2·954	−0·046	R	−1·516	−0·020	A
Gulang	1961	−2·91	−0·0316	R	−2·291	−0·013	A
Total runoff	1962	−2·645	−0·114	R	−2·174	−0·105	A
Inflow into the reservior	1975	−3·659	−0·152	R	−6·0964	−0·031	R

[a] First stage is from 1950 to the change year; the second stage is from the change year to 2003. Z_c and β are test statistics. H_0 is the hypothesis that the data is a sample of n independent and identically distributed random variables. R: rejected; A: accepted; Significance level $\alpha = 0{\cdot}05$.

the changes of annual flow in the Shiyang river were evaluated. The hydrological processes and trends in annual flow for the five tributaries and the main stream (i.e. inflow into the Hongyashan reservoir) of the Shiyang River during the past five decades are shown in Figures 3 and 4, respectively.

Flows for both the tributaries and the Shiyang river exhibit decreasing tendencies. The Pettitt test indicates that the annual flow series for the two tributaries, Xiying and Jingta, have a change point in 1961, while this occurs in 1964 for Zamu, Huangyang and Gulang (Table III). The Mann–Kendall test results show that annual flows for all tributaries have a significant decreasing tendency at the 5% level from 1950 to the change point (1961 for two tributaries and 1964 for three tributaries), but the decreasing tendency in annual flow in the five tributaries is small and not significant at the 5% level after the change point (Table III). As the result of flow declines in the five tributaries, on average, the total flow in mountain outlets varied from $12{\cdot}1 \times 10^8$ m^3 in the 1950s to $9{\cdot}2 \times 10^8$ m^3 in the 1970s and $8{\cdot}2 \times 10^8$ m^3 in the 1990s. The Pettitt test shows that there is a change point in 1962 for the annual total flow in mountain outlets. Moreover, the Mann–Kendall test shows that this decreasing trend for the total flow in mountain outlets is significant at the 5% level for the first series periods, but the decreasing trend in the second period is not significant.

Many researchers have reported that inflow into the Hongyashan reservoir is decreasing over time (Kang *et al*., 2004). Observation data show that flow decreased from $5{\cdot}4 \times 10^8$ m^3 in the 1950s to $3{\cdot}2 \times 10^8$ m^3 in the 1970s and $1{\cdot}1 \times 10^8$ m^3 in the 1990s, and the statistical analysis from the Pettitt test indicates that there is a change point in 1975 for annual flow in the Shiyang river. Furthermore, the Mann–Kendall test indicates that both decreasing trends for periods 1950 to 1975 and 1975 to 2003 are significant at the 5% level. It is obvious that the trend in reduction of inflow into the Hongyashan reservoir is more significant than that of the total flow of the five source tributaries (Figure 4). This can be attributed to human activities in the Wuwei sub-basin. As described above, the amount of diverted surface water has been increasing since the 1950s, especially in the 1990s, when diverted flows constituted about 80% of total annual flows.

Double cumulative curves

It is important to note that the observed records of mountain outlet flows and inflow into the Hongyashan

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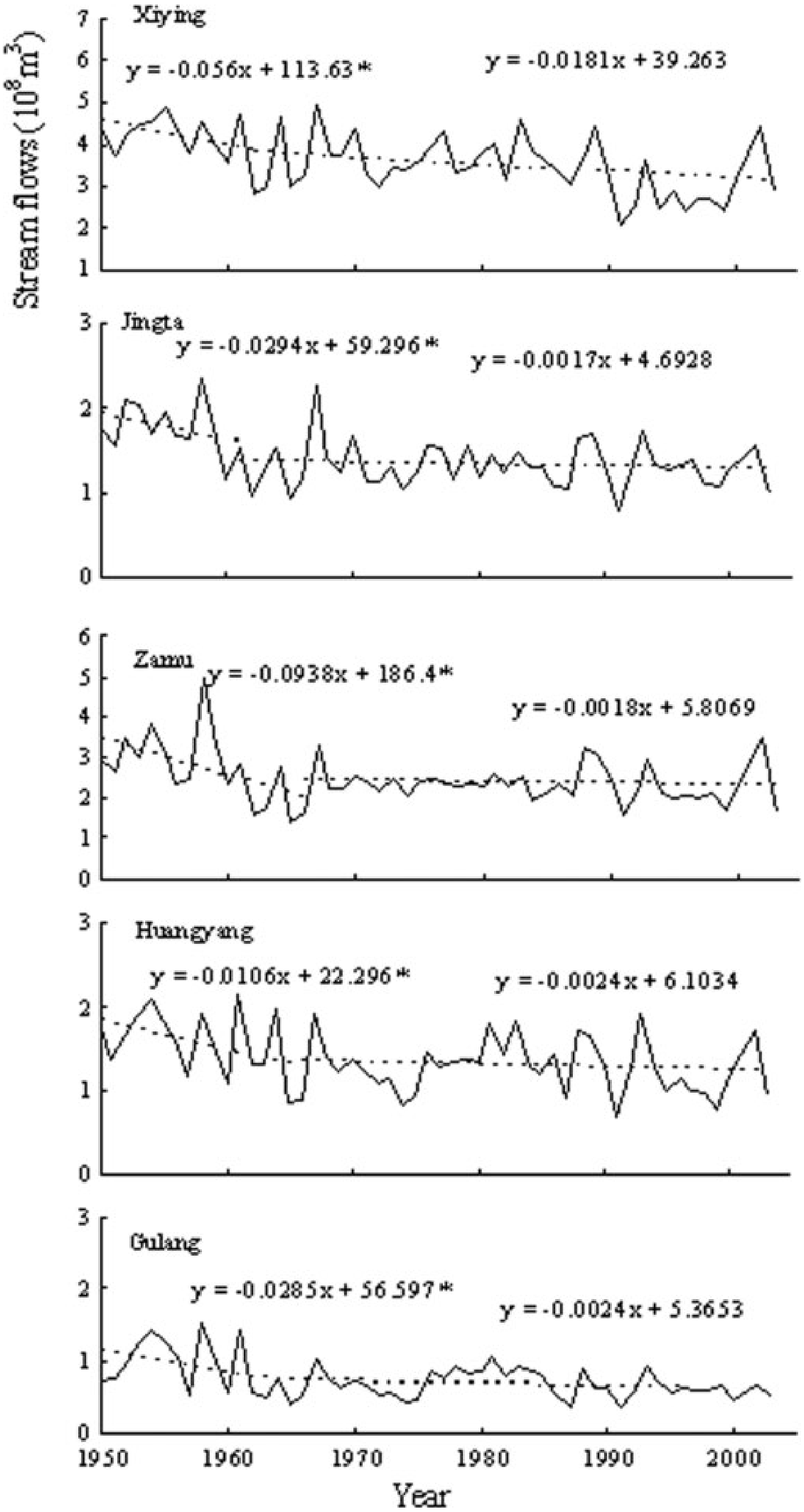

Figure 3. Interannual variations and linear trends of stream flow at Mountains outlets for the five tributaries of the Shiyang River (* denotes the relationships is significant at the 5% level)

reservoir reflect integration of both climatic variation and changes induced by human impacts, primarily additional extraction of irrigation water. In order to determine the time when human activities clearly began to affect stream flows and to evaluate the decrease in stream flows due to human activity and those due to natural variability, the characteristics of double cumulative curves of annual precipitation–upstream flow and upstream–downstream flows was investigated. The change of annual precipitation in the Shiyang river basin is not significant, so in this study the precipitation–runoff coefficients are assumed to vary insignificantly. The two double cumulative curves (Figure 5 and Figure 6) are obtained using Equations (8), (9) and (10). The distribution of cumulative points of

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the precipitation–upstream flow curve before 1970 forms approximately straight lines increasing by year. The standard error of the regression line during this period is approximately zero. We can conclude, then, that the variation in upstream flow before 1970 is a result of natural variation, with the flow obviously largely related to precipitation patterns. Similarly, the double cumulative points of upstream–downstream flows after 1975 deviate from the regression line, signifying that variation in downstream flow before 1975 is a result of natural variation and upstream changes. Consequently, the regression line for data before 1975 is assumed to represent characteristics of river flow under natural conditions.

After 1970, the double cumulative curve for precipitation–upstream flow exhibits a tendency to deviate from the regression line of the natural condition, and the cumulative difference between regressed and observed values increased from $27{\cdot}1 \times 10^8$ m^3 in 1980 to $39{\cdot}8 \times 10^8$ m^3 in 1990 and then $72{\cdot}6 \times 10^8$ m^3 in 2000. The difference between the deviated line and the regression line represents the influence of human activity, and the difference gradually increases after 1970, indicating an increase in severity of human impacts on river flow with time. For the double cumulative curve for upstream–downstream flows, the deviating tendency from the regression line of the natural condition begins in 1975, and the cumulative difference between regressed and observed values increased from $6{\cdot}4 \times 10^8$ m^3 in 1980 to $27{\cdot}0 \times 10^8$ m^3 in 1990 and then $49{\cdot}9 \times 10^8$ m^3 in 2000. The difference gradually increases after 1975, indicating an increase in the severity of human impacts on river flow with time.

Reconstruction of upstream and downstream flows

Two statistical functions, auto-regression (AR) and multi-regression (MR), were developed to reconstruct historical streamflows using precipitation, temperature and flow data. A 20-year data period, from 1951 to 1970, was used to reconstruct upstream flows, and a slightly greater than 25-year period, from 1951 to 1975, was used to reconstruct downstream flows. Figures 7 and 8 compare the simulated flows obtained using the two methods, and shows that the MR model has higher precision than

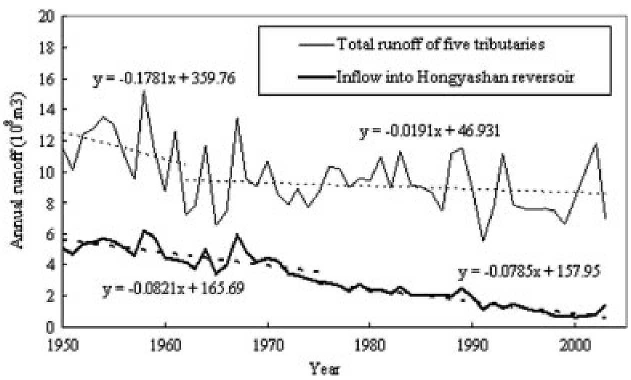

Figure 4. Interannual variations and linear trends of thel five river runoff totals at the mountain outlets, and inflow into the Hongyashan reservoir

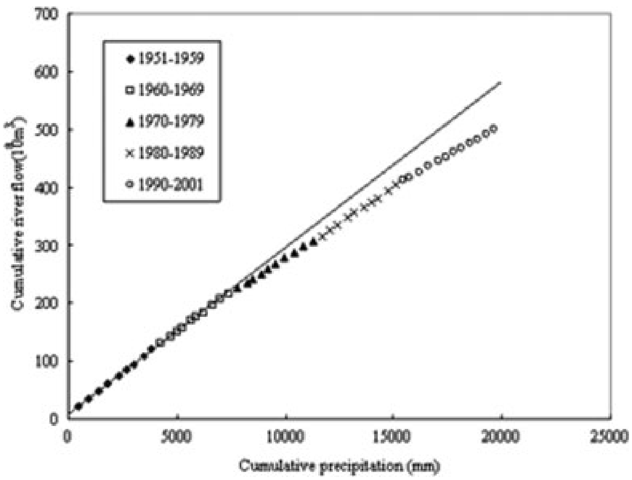

Figure 5. Double cumulative curve for annual precipitation and total runoff of the five tributaries and the regression line estimated by the data from 1950 to 1969

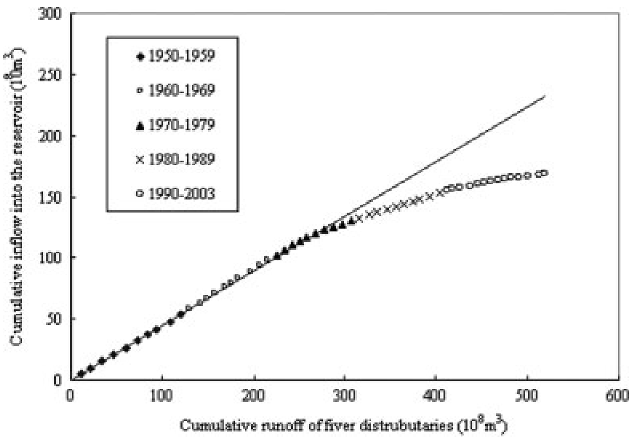

Figure 6. Double cumulative curve for annual total stream flow of the five tributaries and inflow into the Hongyashan reservoir and the regression line estimated by the data from 1950 to 1974

the AR method when simulating both upstream flows and downstream flows. The statistical results (Table IV) show that the root mean squared error (RMSE) for reconstructed flows simulated by the MR model are $0{\cdot}86 \times 10^8$ m^3 and $0{\cdot}38 \times 10^8$ m^3 for upstream flows and downstream flows, respectively. Correspondingly, the relative errors (RE) are 6·63% and 7·42%, demonstrating that the simple regression method used in this study can systematically generate reliable annual stream flow time series, consistent with the annual discharge records for the pre-high-human-activities period. Given that the model generated acceptably accurate results, we then inputted annual precipitation and mean temperature values into the regression model to reconstruct annual upstream flow (total five tributaries flow) records after 1970 (Figure 9). Similarly, using this muti-regression equation, we reconstructed the annual inflow into the reservoir time series for the period after 1975 (Figure 10), the so-called 'high human impact period'. These were done to investigate the effects of climate changes and human activities on flows and to segregate the effect of human activities from the total impacts.

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Table IV. Error statistics of AR and MR models used to simulate the annual upstream and downstream flows[a]

	Upstream flow		Downstream flow	
	AR	MR	AR	MR
RMSE(10^8 m^3)	1·14	0·86	0·57	0·38
RE(%)	12·44	6·63	12·45	7·42
R^2	0·79	0·93	0·8	0·91

[a] AR and MR are the auto-regression model and multi-regression model, respectively. RMSE, RE, R^2 denote, respectively, root mean of squared errors, relative error and coefficient of determination.

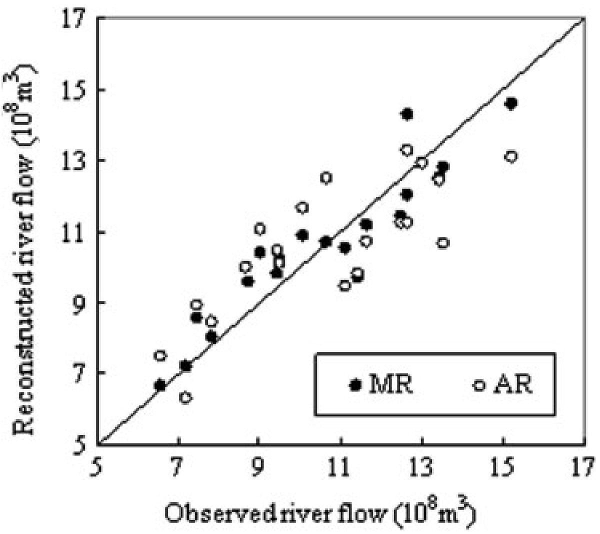

Figure 7. Comparisons of simulated annual total stream flow of the five tributaries using AR and MR models

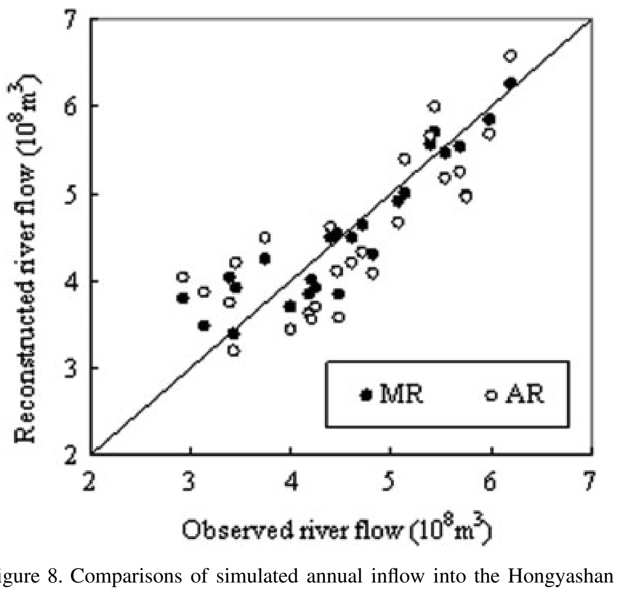

Figure 8. Comparisons of simulated annual inflow into the Hongyashan reservoir using AR and MR models

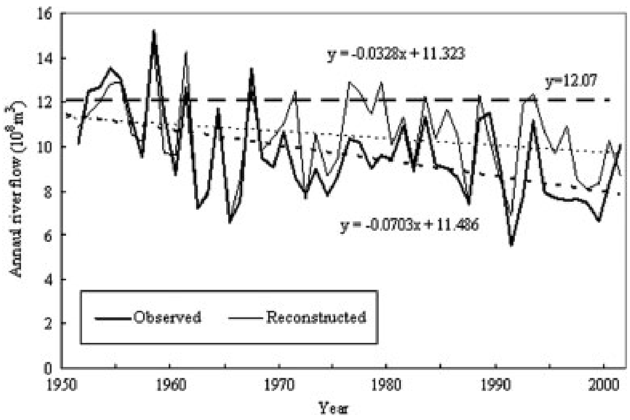

Figure 9. Comparisons of annual total stream flow of the five tributaries and its trend for observed and reconstructed records

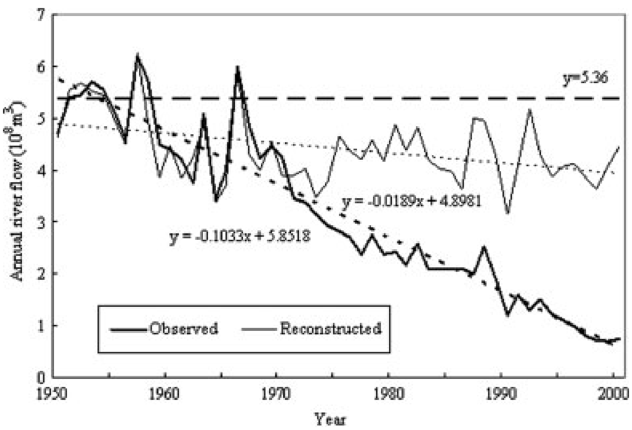

Figure 10. Comparisons of the annual inflow into the Hongyashan reservoir and its trend for observed and reconstructed records

Effect of climate changes and human activities on upstream flow

Effect of climate changes on upstream flow. Reconstructed upstream flow reflects smoothed natural variability and change. It is found that the reconstructed annual upstream flow has a decreasing tendency of $0{\cdot}03 \times 10^8$ m^3 $year^{-1}$, although this is not significant relative to the observed annual decreasing tendency of $0{\cdot}07 \times 10^8$ m^3 $year^{-1}$. Relative to the average discharge ($12{\cdot}07 \times 10^8$ m^3) in the 1950s, the decreased amounts of upstream flow are $2{\cdot}71 \times 10^8$ m^3, $1{\cdot}13 \times 10^8$ m^3, $1{\cdot}53 \times 10^8$ m^3 and $2{\cdot}52 \times 10^8$ m^3, respectively, in the 1960s, 1970s, 1980s and 1990s. Kang *et al.* (1999) simulated the response of stream flows at mountain outlets in the Heihe river basin of north-west China, and showed that runoff will increase by 4% and 7% when temperature rises by 0·5 °C and 1 °C, respectively, under conditions of equal precipitation. Kang *et al.* (1999) also suggests that if the temperature remains the same while precipitation increases 10%, runoff will increase by 5·27%. In accordance with these findings, one can conclude that runoff in arid north-west China is sensitive to temperature and precipitation changes. In the Tianzu station of the Shiyang river basin, both the annual precipitation and mean temperature within the period 1950–1986 have significant decreasing trends, which can reduce annual upstream flow. During the subsequent time period, 1986–2001, temperatures measured at the Tianzu and Gulang stations exhibit increasing trends, which produced more snowmelt and evaporation. In comparison to the period 1950–1986, the decreasing trend for precipitation at these two stations is minor. Consequently, the decrease in stream flows of the five tributaries may be attributed to increasing evaporation.

Effect of human activities on upstream flow. Differences between observed and reconstructed flows reflect the effect of human activities on upstream flow changes. Using Equations (16), (17) and (18), we calculated and quantified the effect of human activities on upstream flows, with the results summarized in Table V. Since 1970, human activities have had a significant influence on upstream flows and the diminished flows are $1{\cdot}77 \times 10^8$ m^3, $0{\cdot}76 \times 10^8$ m^3, $1{\cdot}50 \times 10^8$ m^3, respectively, in the 1970s, 1980s and 1990s. The extents of the influence of human activities on upstream flow are 19%, 7% and 16%. The agriculture policy change of encouraging cultivated land expansion and other production activities increased water extractions in the 1960s and 1970s. It is noted that the influence of human activities on upstream flow is relatively weak for the 1980s, as more precipitation occurred in this period relative to the 1970s and 1990s, which reduced the need to divert water from the river. With economic development and growing populations, the effect of human activities on upstream flow climbed to 16% in the 1990s. The contribution of human activities to total stream diminishment was 60% in the 1970s, but it dropped to 30% and 37% in the 1980s and 1990s, respectively. Consequently, it can be concluded that human activities are a less important factor on upstream flows over the last 20 years, with climate change the predominant factor.

Effect of upstream flow, climate changes and human activities on downstream flow

Effect of climate changes and upstream flow on downstream flow. In contrast to reconstructed records of upstream flows, the reconstructed downstream flow series reflect the combined effects of climate changes and upstream flow. The reconstructed flows exhibit a declining trend of $0{\cdot}019 \times 10^8$ m^3 year^{-1}. Relative to the average annual flow ($5{\cdot}36 \times 10^8$ m^3) in the 1950s, the reconstructed flow decreased by $1{\cdot}11 \times 10^8$ m^3, $1{\cdot}22 \times 10^8$ m^3, $1{\cdot}02 \times 10^8$ m^3 and $1{\cdot}88 \times 10^8$ m^3, respectively, in the 1960s, 1970s, 1980s and 1990s. Although the effects of climate and upstream changes on downstream flow cannot be segregated, the statistical analysis shows there is an obvious linear relationship between reconstructed flow and upstream flow, with coefficient of determination $R = 0{\cdot}91$, with no significant relationship between precipitation/temperature and reconstructed downstream flow. This means that under natural conditions, the annual downstream flow variations depend almost entirely on the upstream flow process. Accordingly, the decreasing tendency of the reconstructed downstream flow can be attribute to the decrease in upstream flow.

Effect of human activities on downstream flow. Although reconstructed and observed flows have decreasing trends, the magnitudes of the flow trends are very different between these two time series. Observed annual flow has a significant declining trend of $0{\cdot}103 \times 10^8$ m^3 year^{-1}, which is stronger than that of the reconstructed flow (Figure 10). This indicates that since 1975, human activities have a strong influence on downstream flow of the Shiyang river. Similar to upstream flow reconstruction, the effect of human activities on downstream flow was quantified using Equations (16), (17) and (18). Relative to the reconstructed data, observed annual flow is underestimated by $1{\cdot}74 \times 10^8$ m^3 year^{-1} from 1975 to 1980, $2{\cdot}14 \times 10^8$ m^3 year^{-1} in the 1980s and $2{\cdot}37 \times 10^8$ m^3 year^{-1} in the 1990s (Table VI). The decreased annual flow induced by human activities accounts for 40%, 49% and 68% of the corresponding reconstructed annual runoff and is responsible for 63%, 68% and 56% of the total decrease in magnitudes, respectively, for the periods 1975–1980, the 1980s and the 1990s. Results show that since 1975, human activities have become the main factor in downstream flow decrease.

The trend difference identified between the reconstructed and observed annual inflow into the Hongyashan reservoir is generally consistent with the overall effect of human activities. With the increasing population and enlargement of the irrigation area, increasingly higher volumes of surface water have been diverted from the Shiyang river and the groundwater system. According

Table V. Effect of human activities on upstream flow and contribution to total upstream decrease[a]

	1970–1979	1980–1989	1990–2001
$W_{ou}(10^8\ m^3)$	10·94	10·51	9·55
$W_{ru}(10^8\ m^3)$	9·17	9·75	8·05
$\Delta W_u(10^8\ m^3)$	1·77	0·76	1·50
R_u (%)	19	7	16
C_u (%)	60	32	37
$1-C_u$ (%)	40	68	63

[a] W_{ou} and W_{ru} denote the annual observed and reconstructed upstream flow respectively; ΔW_u is the annual upstream flow change induced by human activities; R_u is the extent of upstream flow responses to human activities; C_u and $1-C_u$ denote the degree of contribution of human activities and climate changes to upstream flow decreases, respectively. All results are calculated with Equations (11)–(13).

Table VI. Effect of human activities on downstream flow and contribution to total downstream decrease[a]

	1975–1979	1980–1989	1990–2000
$W_{od}(10^8\ m^3)$	2·61	2·20	1·11
$W_{rd}(10^8\ m^3)$	4·35	4·34	3·48
$\Delta W_d(10^8\ m^3)$	1·74	2·14	2·37
R_d (%)	40	49	68
C_d (%)	63	68	56
$1-C_d$ (%)	37	32	44

[a] W_{od} and W_{rd} denote the annual observed and reconstructed downstream flow respectively; ΔW_d is the annual downstream flow change induced by human activities; R_d is the extent of downstream flow responses to human activities; C_d and $1-C_d$ denote the degree of contribution of human activities and climate changes to downstream flow decreases, respectively. All results are calculated with Equations (11)–(13).

to the analysis above, it may be concluded that intense human activities which mainly divert surface and groundwater for irrigation have resulted in significant reductions in downstream flow since 1975. For the sustainable development of the entire Shiyang river basin, particularly the lower reaches, reducing the irrigation area and allocating surface water more rationally is the necessary.

CONCLUSIONS

The following conclusions may be drawn from this study:

1. The study area has become warmer since 1986, with the Mann–Kendall test indicating an increasing tendency of 0·04–0·07 °C year^{-1} in the temperature time-series at the 5% level of significance. Precipitation exhibits decreasing trends at Tianzu, Gulang and Wuwei, but these trends are not significant at the 5% level according to the Mann–Kendall test.
2. The total flow of five tributaries into the Shiyang River has a significant decreasing tendency at the 5% level according to the Mann–Kendall test. Since 1970, human activities have had a significant effect on the flow at mountain outlets, and in the 1970s it was the main factor decreasing the flow, with an estimated 60% contribution to total flow reduction. However, climate changes have predominantly been responsible for flow decreases at mountain outlets in the 1980s and 1990s, although human activities still have an important effect on the flow.
3. Inflow into the Hongyashan reservoir has decreased since the 1950s. The double cumulative curve shows that the effect of human activities in Wuwei began to become significant in 1975, and has increased over time. At the same time, a comparison between reconstructed and observed annual river discharges indicates that the decreased annual flow induced by human activities in the periods 1975 to 1980, the 1980s and the 1990s accounts for 40%, 49% and 68%, respectively, of the corresponding reconstructed annual runoff. Therefore, in the Shiyang river basin, over the last several decades, climate change has played the major role in upstream flow decreases, while human activities account for the major proportion of downstream flow decreases. For the sustainable development of the entire Shiyang river basin, particularly the lower reaches, reducing the impacts of human activities (especially irrigation area) and rational allocation of surface water is critical.

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