

# Periodic changes of stream flow in the last 40 years in Tarim River Basin, Xinjiang, China

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## Abstract:

Using the annual runoff series for the last 40 years from the Tarim River Basin, their periodic properties were analysed and their future trends predicted. Runoff data were collected at five hydrological gauging stations in the three main branches of the Tarim River. An extrapolation method and variance analysis were used to identify periods in annual runoff, and a trend superposition model to predict future changes. Results show that, there is a common period of 17 years in annual runoff changes for all three branches, with Hotan River showing an additional period of 10 years. Based on this trend, it is suggested that the annual runoff of the Tarim River should decrease in the period of 2006–2008, but increase in year 2009, and the flow may possibly begin to decrease significantly in year 2010. The long term trend of runoff in Tarim Basin has followed the global prediction of GCMs, i.e. began to increase in accordance with global increase of air temperature and precipitation in 1990. However, it has shown a local feature of uneven changes among the head streams in the same basin, which needs to be further investigated. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS time series; climate change; prediction; arid inland river basin

Received 25 July 2007; Accepted 22 January 2008

## INTRODUCTION

Water resources are the most important of all the natural resources for social and economic development in arid and semiarid areas (Boehmer *et al.*, 2000). Global warming and change in precipitation patterns caused by CO<sub>2</sub> emission and other human activities change the availability of water resources and in turn affect the natural ecosystems. One of the major consequences caused by climate change is the alternation of regional hydrological cycles and the subsequent changes in stream flow regimes (Xu, 2000). Some recent research results have revealed that both the temperature and precipitation in Tarim River Basin in the last 20 years increased with global climate change (Chen and Xu, 2004), and the hydrological processes in the basin were changed correspondingly. However, the future trends of changes in the hydrological processes and water resources in Tarim River Basin are not fully understood, and such issues are very important for managing water resources in the river basin.

Located in an arid area in north-west China, Tarim River is the largest inland river in China. Tarim River Basin is composed of 114 rivers in nine stream systems surrounding the Tarim Basin, with a catchment area of  $1.02 \times 10^6$  km<sup>2</sup>. Tarim River is mainly recharged by alpine glacier-snow melt water and

rainfall and the long-term average of surface runoff volume is  $3.98 \times 10^{10}$  m<sup>3</sup>. Hydrologically, Tarim River basin represents a closed catchment, where several tributaries drain into its interior, the Tarim depression. In the mean time, it is a unique freshwater ecosystem close to the Taklimakan Desert, the largest of all in China.

The mainstream of Tarim River is 1321 km long. There is no runoff generation in the middle and lower stream areas, only in the upper stream in mountains. It was historically recharged by nine stream systems, but it has successively lost connections with the Qarqan River, Keriya River, Dina River, Kaxgar River, Kaidu-Kongque River, and Ogan River. Among the three main headstreams, the Aksu River is currently the main source recharging the mainstream of Tarim River, and the recharging proportions of the Aksu River, Hotan River and Yarkand River are 73.2%, 23.2% and 3.6%, respectively (Chen *et al.*, 2003). These three rivers play an important role in the oasis economic development and the desert ecological conservation in Tarim River Basin.

After analysing the hydrologic processes of the three main headstreams of Tarim River, the periodic change in the stream flow of Tarim River is examined; the trend of future change in stream flow of the river is predicted using a trend superposition model of hydrological time series. It is hoped that these results can serve as a reference for decision making in water resources management and sustainable social, ecological and economic development in Tarim River Basin.

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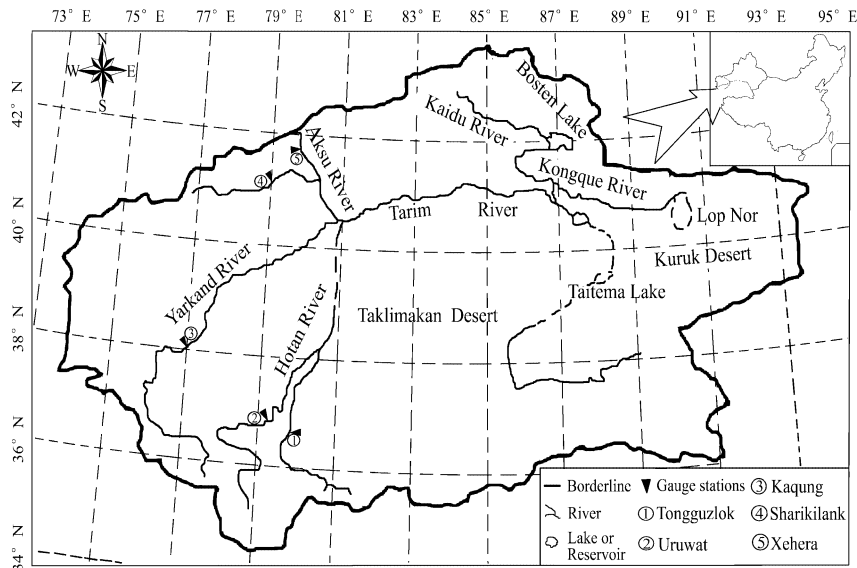


Figure 1. Sketch map of Tarim River Basin

DATA AND METHODS

Because Tarim River basin covers more than two-thirds of the area of Xinjiang Autonomous Region and the impact of climate change usually involves large area, temperature and precipitation data for Xinjiang are employed. The temperature data from 77 climatological stations and the precipitation from 61 rain gauges are used in this study. The monthly runoff data for 1957–2004 were collected from five hydrological stations in the headstreams of Tarim River (Figure 1 and Table I). The Shrikilank and Xehera stations are on the Aksu River, Tongguzlok and Uruwat stations are located on the Hotan River, and Kaquang station on the Yarkand River. All stations are located in the mountains where human disturbance is negligible.

*Extrapolation method of periodic variance analysis of hydrological time series*

The rationale and methods of the extrapolation method of periodical variance analysis of hydrological time series are as follows. It is supposed that the time series of annual runoff volume  $X(t)$  is divided into  $r$  groups according to its periodical length  $n$ , the mean square within a group is derived by dividing the quadratic sum of the group ( $Q_1$ ) with the corresponding first freeness ( $f_1$ ), and the mean square among the groups is derived by dividing the quadratic sum of the groups ( $Q_2$ ) with the corresponding first freeness ( $f_2$ ). It is assumed that  $F = D_2/D_1$ , where,  $D_1$  is the difference within a group, and  $D_2$  is the difference among the groups. The difference among the groups is significant if the  $F$  value is high enough, which means that there is a significant period.

*Periodic trend superposition prediction model*

It is assumed that the change of stream flow has a certain trend level in addition to its periodic change. Therefore, the trend of change in water resources can

be predicted using the periodic trend superposition prediction model (Zuo and Guo, 2004). The rationale and the methods are that the expectation value during the period  $T + \tau$  can be expressed as

$$\mu_{T+t} = a_T + b_\tau + \sigma_{T+\tau} \tag{1}$$

where  $a_T$  is the average during the period  $T$ ,  $b_\tau$  is the slope during the period, and  $\sigma_{T+t}$  is the seasonal increment during the period  $T + \tau$ .

There are two steps to develop the prediction model based on the historical data. The first step is to estimate the parameters  $\hat{a}_T$ ,  $\hat{b}_T$  and  $d_{T+\tau}$  ( $\tau = 1, 2, \dots, M$ ) based on the time series data of the integrated periods, and the parameters in the future are predicted. The second step is to update the prediction model using the data of an incomplete period, and the corresponding parameters are predicted.

In the first step, the time series data of at least two integrated periods are needed; the data sample  $T$  must be a multiple of  $M$  (in practical calculation,  $M \times N$  samples are used only, and the time series data of the half-baked period are used to update the prediction model after the model is developed).  $N$  denotes the number of integrated periods contained in the time series data, that is  $N = T/M$ , and then the integrated periods are rounded. The  $T$  time series data are divided into  $N$  groups. In calculation, the averages of the first period and the last period (period  $N$ ) are derived, and the initial slope ratio is estimated and the average expectation value at time series  $T = 0$  of the corresponding period is calculated with the following equations:

$$\bar{b}_0 = (\bar{x}_N - \bar{x}_1)/(T - M) \tag{2}$$

$$a_0 = x_1 - [\text{int}(M/2) + 0.5]\bar{b}_0 \tag{3}$$

According to the seasonal averages of  $\bar{a}_0$  and  $\bar{b}_0$  during the period  $T$ , the seasonal increments during the periods from  $t = 1$  to  $T$  are estimated with  $\bar{a}_t = x_t + \bar{a}_t$ . The

seasonal ratios are revised by subtracting the seasonal increments from the averages of seasonal ratios.  $\hat{d}_t = \bar{d}_1 - \bar{d}$  ( $t = 1, 2, \dots, M$ ), it is assumed that  $\hat{a}_0 = \bar{a}_0$ ,  $\hat{b}_0 = \bar{b}_0$ , and the following three parameters during the period from  $t = 1$  to  $T$  are estimated:

$$\hat{a}_t = \alpha(x_t - \hat{d}_t) + (1 - \alpha)(\hat{a}_{t-1} + \hat{b}_{t-1}) \quad (4)$$

$$\hat{b}_t = \beta(\hat{a}_t - \hat{a}_{t-1})(1 - \beta)\hat{b}_{t-1} \quad (5)$$

$$d_{t+M} = \gamma(x_t - \hat{a}_t) + (1 + \gamma)\hat{b}_t \quad (6)$$

The seasonal increments during all the periods are standardized so as to let their sum be zero. The averages should be derived first:

$$v_i = \frac{1}{M} \sum_{j=1}^M \hat{d}_{(j-1)M+i} \quad (j = 2, 3, \dots, n) \quad (7)$$

The seasonal increments are revised with the following equation:

$$d_{(j-1)M+i} = \hat{d}_{(j-1)M+i} - v_i \quad (j = 2, 3, \dots, N + 1; i = 1, 2, \dots, M) \quad (8)$$

Thus, the parameters  $\hat{a}_T$ ,  $\hat{b}_T$  and  $d_{T+\tau}$  ( $\tau = 1, 2, \dots, M$ ) in the seasonal superposition model are estimated, and the prediction model of period  $T$  to period  $\tau$  in the future is developed:

$$\hat{x}_T(\tau) = \hat{a}_T + \hat{b}_T\tau + d_{T+\tau} \quad (9)$$

Other data during the half-baked period are used to update the prediction model mentioned above, and the updated equations are as follows:

$$\begin{aligned} \hat{a}_{T+i} &= \alpha(x_{T+i} - d_{T+i}) \\ &+ (1 - \alpha)(\hat{a}_{T+i-1} + \hat{b}_{T+i-1}) \\ \hat{b}_{T+i} &= \beta(\hat{a}_{T+i} - \hat{a}_{T+i-1}) + (1 - \beta)\hat{b}_{T+i-1} \\ &(i = 1, 2, \dots, N_1) \end{aligned} \quad (10)$$

$$d_{T+M+i} = \gamma(x_{T+i} - \hat{a}_{T+i}) + (1 - \gamma)d_{T+i}$$

The seasonal increments are revised using the following equation:

$$d_{T+N_1+\tau}^* = d_{T+N_1+\tau} - d \quad (\tau = 1, 2, \dots, M) \quad (11)$$

The prediction model of  $T + N_1$  period to period  $\tau$  in the future can be derived using the updated values:

$$\hat{x}_{T+N_1}(\tau) = \hat{a}_{T+N_1} + \hat{b}_{T+N_1}\tau + d_{T+N_1+\tau}^* \quad (\tau = 1, 2, \dots, M) \quad (12)$$

The developed integrated prediction model of period  $T$  to period  $\tau$  is:

$$\hat{x}_T(\tau) = \hat{a}_T + \hat{b}_T\tau + d_{T+\tau} \quad (\tau = 1, 2, \dots, M) \quad (13)$$

*Kendall's  $\tau$  for association between two variables*

In this investigation, Kendall's  $\tau$ , which is often useful for time series that are not an independent, identically

distributed normal random variable (Yue *et al.*, 2002; Yue and Wang, 2004) is employed to detect the possible association between hydrological variables and ENSO. In Kendall's  $\tau$  approach, the test statistic is given as

$$Z_c = \frac{S'}{\sqrt{\text{Var}(S')}} \quad (14)$$

in which

$$\begin{aligned} \text{var}[S'] &= \frac{n(n-1)(2n+5) - \sum_x t_i(t_i-1)(2t_i+5) - \sum_y s_i(s_i-1)(2s_i+5)}{18} \\ &+ \frac{\left[ \sum_x t_i(t_i-1)(t_i-2) \right] \cdot \left[ \sum_y s_i(s_i-1)(s_i-2) \right]}{9n(n-1)(n-2)} \\ &+ \frac{\left[ \sum_x t_i(t_i-1) \right] \cdot \left[ \sum_y s_i(s_i-1) \right]}{2n(n-1)} \end{aligned} \quad (15)$$

where  $S'$  is the Kendall sum, and is estimated as  $S' = L - M$ , in which  $L$  is the number of cases where  $y_i > y_j$  ( $i > j$ ), and  $M$  is the number of cases where  $y_i < y_j$  ( $i < j$ ). The null hypothesis is rejected at significant level  $\alpha$  if  $|Z_c| > Z_{1-\alpha/2}$ , where  $Z_{1-\alpha/2}$  is the value of the standard normal distribution with a probability of exceeding  $\alpha/2$ .

The strength of the association between two time series is measured by  $\tau_a$  or  $\tau_b$  ( $\tau_b$  handles ties), which are estimated as follows,

$$\tau_a = \frac{S'}{n(n-1)/2} \quad (16)$$

$$\tau_b = \frac{2S'}{\sqrt{\{n(n-1) - \sum_{i=1}^{n_x} t_i(t_i-1)\} \{n(n-1) - \sum_{i=1}^{n_y} s_i(s_i-1)\}}} \quad (17)$$

in which  $n_x$  is the number of ties in the  $x$ -rankings, and  $n_y$  is the number of ties in the  $y$ -rankings. Kendall's  $\tau_a/\tau_b$  only takes on values between  $-1$  and  $1$ . The sign indicates negative or positive relationship, and the absolute value indicates the strength of the relationship.

*Wilcoxon test for association between two variables*

Although Kendall's  $\tau$  may be used to test the strength of the association between hydrological processes and ENSO, it cannot identify the relationship between the hydrological processes and different ENSO phases. In order to further investigate the detailed correlation between hydrological variables and different ENSO episodes, the nonparametric Wilcoxon test is employed in this study (Giannini *et al.* 2001). The Wilcoxon test statistic is given as follows:

$$Z_W = \frac{W - E(W)}{\sqrt{\text{var}(W)}} \quad (18)$$

in which

$$W = \sum_{i=1}^n \text{rank}(ENSO_i) \quad (19)$$

$$E(W) = \frac{n(n+m+1)}{2} \quad (20)$$

$$\text{var}(W) = \frac{mn(n+m+1)}{12} \quad (21)$$

Generally,  $n < m$ , where  $n$  is the number of warm, or cold years, and  $m$  is the number of normal years. The hydrological variable is ranked separately for warm and normal, or cold and normal conditions. A Wilcoxon two-sample sum statistic is applied to the ranks, and the hypothesis is stated as follows:

$$H_0 : \mu_{Nino} = \mu_{Neutral} = \mu_{Nina}$$

(No tele-connection between El Niño and Southern Oscillation (ENSO) and the hydrological process)

vs  $H_1$  : At least two of the means are different

(Teleconnection exists between ENSO and the hydrological process) in which  $\mu_{Nino}$ ,  $\mu_{Neutral}$ ,  $\mu_{Nina}$  are the variable means for the periods of El Niño, normal, and La Niña phases, respectively. Hydrological process is defined as being affected by El Niño (or La Niña) phase when  $\mu_{Nino}$  is significantly different from  $\mu_{Neutral}$  (or  $\mu_{Nina}$  is significantly different from  $\mu_{Neutral}$ ). Hypothesis  $H_0$  is rejected if  $|Z_W| > Z_{1-\alpha/2}$ , where  $Z_{1-\alpha/2}$  is the  $1 - \alpha/2$  point on the standard normal probability distribution, and  $\alpha$  is the significance level.

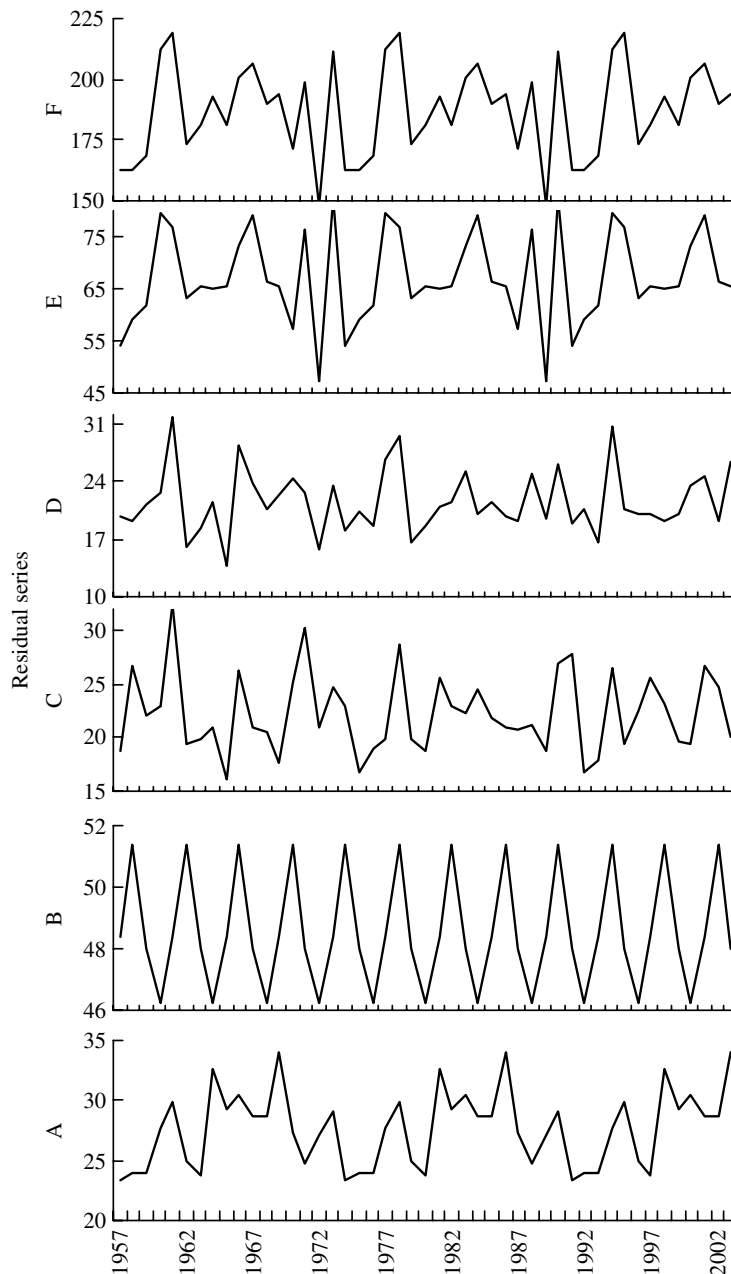


Figure 2. Periods of stream flow change in Tarim River Basin

Table I. Hydrological stations and hydrological eigenvalues on the Tarim River Basin

River name	Hydrological station	Catchment area (km <sup>2</sup> )	Annual runoff volume (10 <sup>8</sup> m <sup>3</sup> )	Runoff composition (%)		
				Glacier melt	Snow melt/rainfall	Base flow (groundwater)
Aksu River	Sharikilank	19 166	27.67	24.7	45.1	30.2
	Xehera	12 816	48.67	52.4	30.4	17.2
Yarkand River	Kaung	50 248	65.43	64	13.4	22.6
Hotan River	Tongguzlok	14 575	22.27	64.9	17	18.1
	Uruwat	19 983	21.39	54.1	22.1	23.8

Table II. Stream flow change periods in the Tarim River Basin

Headstream	Name of hydrological station	Period	F value	Degree of confidence	Correlation coefficient
Aksu River	Sharikilank	17	1.0221	0.53754	0.76432
	Xehera	4	0.9046	0.55325	0.70355
Hotan River	Tongguzlok	10	1.9999	0.93263	0.73134
	Uruwat	12	2.3666	0.96395	0.65309
		17	2.129	0.97387	0.84177
Yarkand River	Kaung	17	2.0751	0.9589	0.84007
Inflows from debouchures of headstreams		17	1.9377	0.94257	0.86834

ANALYSIS OF THE RESULTS

Periods of stream flow

Analysis of the hydrological processes in Tarim River Basin over the last 40 years reveals that the inflows of headstreams to the Tarim River in recent years (20) exhibit an increasing trend (Chen and Xu, 2004). However, the trend in the future is unknown. The extrapolation method of variance analysis of time series was used to analyse the change periods of the stream flow data measured at the hydrological stations in the headstream areas of Tarim River.

Analysis of the results (Figure 2 and Table II) reveal that, among the three main headstreams of Tarim River, the period of change for stream flow of the Aksu River is 17 years; that of the Hotan River is unsure. At Tongguzlok Hydrological Station, a representative hydrological station of the Yurungkax River, there is a single 10 year period. The change periods at Uruwat Hydrological Station, a representative hydrological station of the Karakax River, are 12 and 17 years, although the latter is dominant. The change period of the Yarkand River is a single one at 17 years. The change period of runoff volume from the mouths of the three main headstreams of the Tarim River is a common one at 17 years. In short, the 17 year period of change is dominant for stream flow from the three main headstreams.

It is important for managing water resources in Tarim River Basin to analyse the future trends in stream flow of the three headstreams based on analysis of the change periods of the stream flow data measured at the hydrological stations in the river basin.

Therefore, the inflows of headstreams of Tarim River were simulated and predicted using the trend superposition model based on analysis of the stream flow change periods.

Trends in stream flow change

The future trends in stream flow of the three headstreams of Tarim River were analysed using the periodic trend superposition model based on the stream flow change periods of the three headstreams.

First, the data of the 17 year period of hydrological time series of stream flow of the headstreams during the period of 1957–2004 were input into the model, and the following important parameters of the periodic trend superposition model of the three headstreams of Tarim River were derived:

$$\begin{aligned}
 &\text{smoothed periodic average parameter } \alpha = 0.01000000; \\
 &\text{smoothed slope rate parameter during the period } \beta = 0.01000000; \\
 &\text{smoothed periodic increment parameter } \gamma = 0.01000000; \\
 &\text{periodic average } A = 200.98443995; \\
 &\text{slope } B = 0.51320681.
 \end{aligned}$$

Second, the prediction model was developed:

$$X(\tau) = 200.98443995 + 0.51320681\tau + d_{t+\tau}$$

where  $X(\tau)$  is the predicted result,  $\tau$  is the period, and  $d_{t+\tau}$  is the periodic increment or decrement.

The time series data for annual runoff volumes of the headstreams of the Tarim River were fitted to the model. The fitted results (Figure 3) reveal that the fitting error in the predicted mean square of total annual runoff volumes of the headstreams is 9.71; the difference between the

Table III. Predicted values of the total annual runoff volumes from headstreams of the Tarim River in different years

Year	2005	2006	2007	2008	2009	2010
Total annual runoff volume of the headstreams ( $10^{10} \text{ m}^3$ )	2.2631	2.0563	2.0698	1.9830	2.2643	1.7383

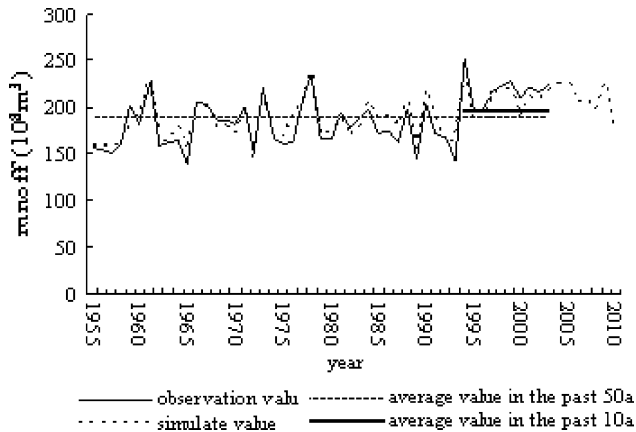


Figure 3. Measured and fitted values of annual runoff volumes of headstreams of Tarim River

measured and fitted values is very small, indicating that the fitted results are good.

The test of the fitted model values against the measured values provides confidence degree of the model. The focus in this paper is not on fitting the historical data, but also on predicting the stream flow regime in the river basin in the future using the models, so as to provide a reference for rational planning and management of the basin. The future stream flow change was simulated and predicted using the models. After analysing the hydrological data during the integrated periods with the trend superposition model, the preliminary prediction model was developed, and then the model was updated using the hydrological data obtained during the half-baked period. The predicted values of annual runoff volumes from the mouths of the headstreams of the Tarim River in the future were derived based on the calculated results using the model (Table III and Figure 3).

The predictions showed that the total annual runoff volume of the headstreams was  $2.2631 \times 10^{10} \text{ m}^3$  in 2005 and similar to that in 2004, but would be subject to a decreasing trend in the following 3 years; a high flow year would occur in 2009, and then the total annual runoff volume of the headstreams would experience a decreasing trend. Comparing the total annual runoff volume of the headstreams of Tarim River in past years, 2005 and 2009 were and will be years with relatively high flows, and the total annual runoff volume was and will be about 20% higher than the multiannual average. The total annual runoff volume in 2006, 2007 and 2008 was predicted to be 9%, 10% and 5% higher than the multiannual average, although it would be subject to a decreasing trend. It would, however, decrease sharply in 2010 to 7% less than the multiannual average and to 10% than the 10-year average since 1994.

## DISCUSSION

### *Periodic change of temperature, precipitation and stream flow*

In climate change, temperature and precipitation are the most significant indicating factors. Global warming caused by the increase in concentrations of  $\text{CO}_2$  and other trace gases has been agreed upon by the scientific community (Houghton *et al.*, 2001; Kamga, 2001). However, opinions about the precipitation change trend related to such warming vary. In arid and semiarid areas, stream flow and water resources are extremely changeable, and a slight change of temperature and precipitation can result in a significant change of stream flow. In the Tarim River Basin, an arid continental river basin, the ecological environment is particularly vulnerable, its response to global climate change is sensitive and strong, and a slight change of climatic factors, such as temperature and precipitation, can result in a significant change of stream flow. Climatic warming corresponding to global warming has occurred in Xinjiang over the last 50 years (Wang and Ye, 1995), however, the precipitation change trend related to such warming is not certain, and the change trends and physical mechanisms of the time series of temperature, precipitation and stream flow are not well understood yet. There are two different opinions about the change trend of precipitation in Xinjiang over recent years. One opinion considers that there is a warming–drying trend in Xinjiang; such an opinion, however, is mainly derived from indirect evidence, such as the shrinkage of modern glaciers and lakes and the expansion of land desertification. Another opinion considers that there is a warming–wetting trend in Xinjiang, and such a trend is directly derived from the comparison and analysis of precipitation data observed by meteorological stations (Shi and Zhang, 1995; Jiang *et al.*, 2002). On comparison, it is found that the average annual precipitation in north Xinjiang during the period 1987–1996 increased by 16.2% and 18.0%, respectively over that in the previous two decades (1967–1976 and 1977–1986); it increased to 228.8 mm. The average annual precipitation in the Tarim River Basin in south Xinjiang also increased, by 23.2% and 30.1%, respectively over that in the previous two decades, to 94.5 mm, and the temperature also showed a monotone increasing trend at a rate of 5% (Chen and Xu, 2004).

Tarim River is mainly recharged by rainfall, seasonal snow cover melt water and alpine glacier-snow melt water, and the climatic factors directly affecting the recharge of the river are precipitation and temperature. In order to further prove the intrinsic hypostasis of the periodic change of stream flow, the averages of temperature and precipitation in the three main headstream

Table IV. Analysed results of the change periods of average annual precipitation and temperature in headstream areas of Tarim River Basin

Area		Precipitation				Temperature			
River	Name of hydrological station	Period	F value	Confidence degree	Correlation coefficient	Period	F value	Confidence degree	Correlation coefficient
Aksu River	Sharikilank	19	1.9958	0.9493	0.7885	13	0.9331	0.4725	0.6464
	Xehera	14	3.0461	0.9951	0.7382	14	0.9459	0.4789	0.9173
Hotan River	Uruwat	19	1.6229	0.8703	0.7716	19	2.1797	0.9497	0.9901
Yarkand River	Kaung	Short data series without representation				17	2.3888	0.9808	0.9772

areas of the Tarim River over the past 50 years were analysed. The results reveal that there is a 17 year temperature change period in the Yarkand River Basin (the precipitation series is short and has no representation); there is a 19 year precipitation and temperature change period in the Hotan River Basin; the precipitation and temperature change period in the Aksu River Basin is complicated; as a whole, the precipitation change period varies in the range of 14–19 years. There is a stable 13 year or 14 year temperature change period in the study area (Table IV). Analysing the synthetic effect of the change of precipitation and temperature, the change period affecting stream flow in the rivers is the 17 year dominant period.

*Relations between temperature, precipitation and El Nino events*

El Nino events are a main driving factor for climatic and hydrological abnormalities, and there are many kinds of relations between El Nino events and hydrological fluctuations. For example, Mechoso and Iribarren (1992) found a relationship between ENSO and stream flow in Negro and Uruguay River Basins. Generally, negative abnormalities in stream flow are related to cold periods near the equator in the Pacific Ocean, whereas positive ones are related to warm periods. Bordi and Sutura (2001) found similar relationships in 2001. After researching the relations between the El Nino events and precipitation in south-east Asia and China, Kane pointed out that precipitation in China is different from other regions and the relations between El Nino events and droughts are not well defined (Kane, 1999). In Tarim River Basin, the seasonal and annual change of precipitation is significant. The relations between El Nino events and hydrological processes were investigated, and Table V shows both Pearson correlation coefficients and Kendall's  $\tau$  between Southern Oscillation Index (SOI) and the precipitation/temperature time series. It shows that both parametric and nonparametric tests accept the hypothesis  $H_0$ . In other words, there is no significant association between SOI and precipitation/temperature time series. Similar results for the stream flow time series on the three tributaries and along the mainstream of Tarim River are also given in Table VI. All stream flows show no significant correlation with the SOI time series. These results suggest that the periodic changes in temperature, precipitation and stream flow in the study area are

possibly caused by a complicated correlation between ENSO stages and local climatic factors.

In order to further research the effects of ENSO cold, warm and moderate periods near the equator on the stream flow change periods, the hydrological time series was divided into three samples, and each sample homologizes a stage of the ENSO cold, warm or moderate periods. The results reveal that there are no differences

Table V. Pearson cross-correlation coefficient and Mann-Kendall  $\tau_a/\tau_b$  between SOI and precipitation/temperature

Item	Pearson		Kendall		
	$r_c$	$H_0$	$\tau_a/\tau_b$	$Z_c$	$H_0$
Temperature	-0.191	A	-0.122	-1.184	A
Precipitation	-0.163	A	-0.068	-0.646	A

Table VI. Pearson cross-correlation coefficient and Mann-Kendall  $\tau_a/\tau_b$  between SOI and stream flow from the three tributaries

River	Pearson		Kendall		
	$r_c$	$H_0$	$\tau_a/\tau_b$	$Z_c$	$H_0$
Aksu R.	-0.208	A	-0.116	-1.073	A
Yarkand R.	0.041	A	0.083	0.774	A
Hotan R.	0.125	A	0.134	1.235	A

Table VII. Wilcoxon test of precipitation/temperature time series

Item	El Niño		La Niña	
	$W^*$	$H_0$	$W^*$	$H_0$
Temperature	1.684	A	1.045	A
Precipitation	1.198	A	0.936	A

Table VIII. Wilcoxon test of stream flow from the three tributaries

River	El Niño		La Niña	
	$W^*$	$H_0$	$W^*$	$H_0$
Aksu R.	0.412	A	-0.656	A
Yarkand R.	-1.160	A	-0.930	A
Hotan R.	-1.871	A	-0.701	A

in temperature, precipitation and stream flow at the different ENSO stages. The results of Wilcoxon tests of the time series for precipitation, temperature and stream flow also reveal that almost all the time series meet the  $H_0$  assumption (Tables VII and VIII). These reveal that the effect of ENSO events on the climate in the study area is low. There is no significant correlation between the hydrological time series and the ENSO events.

## CONCLUSIONS

The change of inflow from the mountainous regions to the Tarim River Basin is mainly affected by global climate change and the periodic change of stream flow in the river basin. In this study, an extrapolation method of variance analysis of hydrological time series was used to derive the change periods, and a trend superposition model was used to fit and predict future trends in hydrological processes. The fitted results for time series data of annual runoff volumes in the headstreams of the Tarim River show that the fitting error of the predicted mean square of total annual runoff volume of the headstreams is 9.71; the difference between the measured and modelled values is very small, confirming that the fitted results are good.

Analysis of the stream flow change periods for the headstreams of the Tarim River reveal that, among the main headstreams, the stream flow change period of the Aksu River is 17 years; that of the Yurungkax River, a tributary of the Hotan River, is stabilized at 10 years, but the change periods of the Karakax River are 12 and 17 years, in which the 17-year change period is dominant; the complexity of the change periods is possibly related to the effect of the Uruwat Reservoir on the natural stream flow. The change period of the Yarkand River is stabilized at 17 years. The change period of runoff volume from the debouchures of the three main headstreams of the Tarim River is also stabilized at 17 years. Analysis of the averages of annual temperature and precipitation in the three main headstream areas of Tarim River over the last 50 years shows that there are the significant periods in the change of precipitation and temperature in Tarim River Basin. The precipitation change period in the range 14–19 years, that of temperature over 13 to 14 years. The effect of ENSO events on climate change in the study area is very small, and there is no significant correlation between hydrological time series and ENSO events.

The predicted results for stream flow change in the headstreams of the Tarim River in the future using the trend superposition model revealed that the total annual runoff volume of the headstreams in 2005 was 20% higher than the multiannual average, and it would experience a decreasing trend during the period 2006–2008 but remain higher than the multiannual average. A high flow year is predicted to occur in 2009, and the total annual runoff volume of the headstreams will be similar to that during the period of 2004–2005. A low flow period may possibly occur from 2010. The stream flow of

the headstreams of the Tarim River will sharply reduce. Such trends should be taken into account to work out corresponding measures for managing water resources and to reduce further changes to the hydrological regime and its effect on regional social and economic development and the ecological conservation of the Tarim River Basin.

## ACKNOWLEDGEMENTS

This work was supported by the Knowledge Innovation Project of the Chinese Academy of Sciences ‘Water resources in Xinjiang: formation, transformation and control (Grant No. KZCX2-YW-127)’ and ‘Water Resources Utilization and Integrated Management Demonstration in Tarim River Basin (Grant No. 90502004)’, and the National Natural Science Foundation of China (Grant No. 30500081, 40672171).

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