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Impacts of temperature and precipitation on runoff in the Tarim River during the past 50 years

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Abstract: The relationship between climate change and water resources in the Tarim River was analyzed by combining the temperature, precipitation and streamflow data from 1957 to 2007 from the four headstreams of the Tarim River (Aksu, Hotan, Yarkant and Kaidu rivers) in the study area. The long-term trend of the hydrological time series including temperature, precipitation and streamflow were studied using correlation analysis and partial correlations analysis. Holt double exponential smoothing was used to fit the trends between streamflow and the two climatic factors of Aksu River, Hotan River and Yarkant River. The streamflow of the main stream was forecasted by Autoregressive Integrated Moving Average Model (ARIMA) modeling by the method of time series analysis. The results show that the temperature experienced a trend of monotonic rising. The precipitation and runoff of the four headstreams of the Tarim River increased, while the inflow to the headstreams increased and the inflow into the Tarim River decreased. Changes of temperature and precipitation had a significant impact on runoff into the four headstreams of the Tarim River: the precipitation had a positive impact on water flow in the Aksu River, Hotan River and Kaidu River, while the temperature had a positive impact on water flow in the Yarkant River. The results of Holt double exponential smoothing showed that the correlation between the independent variable and dependent variable was relatively close after the model was fitted to the headstreams, of which only the runoff and temperature values of Hotan River showed a significant negative correlation. The forecasts by the ARIMA model for 50 years of annual runoff at the Allar station followed the pattern of the measured data for the same years. The short-term forecasts beyond the observed series adequately captured the pattern in the data and showed a decreasing tendency in the Tarim River flow of 3.07% every ten years. The results showed that global warming accelerated the water recharge process of the headstreams. The special hydrological characteristics of the arid area determined the significant association between streamflow and the two climatic factors studied. Strong glacier retreat is likely to bring a series of flood disasters within the study area.

Keywords: Tarim River Basin; climate change; hydrological change; water resources; streamflow

One of the most valuable resources in arid areas is water. It is the foundation of oasis ecosystem development and stability. Water is also an important environmental factor in arid areas. The streamflow trends and hydrological responses to climatic change within the Tarim River Basin have received much attention because of the basin's unique geographical location and the fragile ecological system (Yang *et al.*, 2004). Developing water resources and protecting the environment of the Tarim River Basin have strategic significance not only for the survival and development of the watershed but also for the western development strategy (Sun *et al.*, 2009). Hydrological and natural ecological conditions are changing significantly because of the utilization of water resources and high intensity of human economic and social activities over the past 50 years (Chen *et al.*, 2004). Recently, the response of water resources and the natural environment to climate changes have been widely researched

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within the Tarim River Basin (Chen *et al*., 2009; Ye *et al*., 2009a, b; Zhang *et al*., 2010; Zhou *et al*., 2010). The Tarim River is a pure dissipative inland river with no production flow, and it entirely relies on water supply from its headstreams in the mountains. The surface runoff is 3.92 × 10^{10} m^3/a, which comes mainly from snow-melt water resources on the western, southern and northern mountains (Hao *et al*., 2006). Analysis of the relationship between climate change and hydrological processes in the Tarim River Basin is necessary in order to predict future flow rates and water availability.

Previous studies have shown that annual average temperature and precipitation in the Tarim River Basin have increased significantly (Xu *et al*., 2007; Gao *et al*., 2008; Zhang *et al*., 2008; Duan *et al*., 2009). Meanwhile, the runoff has fluctuated with changes in temperature and precipitation (Tao *et al.,* 2007; Zhang *et al*., 2008). Streamflow in the headwaters has increased significantly, which might be related to the increased snow-melt water caused by rising temperature (Shi, 2001; Shen *et al*., 2009). The average temperature in the Tarim River Basin has been rising, most noticeably since the late 1970s, and precipitation over this period has shown a fluctuating but significant upward trend (Li *et al*., 2007). The discharge from headstreams had increased for many years because of increasing precipitation and temperature (Fu *et al*., 2009). But the annual runoff in the mainstream of the river has tended to slightly decrease over the past 50 years (Wang *et al.,* 2003). The annual runoff in the Tarim River may be affected by temperature changes, meanwhile, changes in precipitation impact the runoff of headstreams. However, the response of runoff to temperature and precipitation and the relationship between them is not clearly understood. This study set out to improve that understanding, through combining hydrological, temperature and precipitation data from the last 50 years, and analyzing the characteristics of the hydrological process and the response of runoff to temperature and precipitation changes in the Tarim River Basin.

1 Study area

The Tarim River Basin (39°00'–41°40'N, 80°30'–88°30'E) is the generic term for the combination of the catchments of the Aksu River, Kashgar River, Yarkand River, Hotan River, Kaidu–Peacock River, Dina River, Weigan River, Kuqa River, and Keriya River, composed of 114 rivers in 9 stream systems (Duan *et al*., 2009). The total area of the Tarim River Basin is 1.02 × 10^6 km^2 (996,000 km^2 within Xinjiang), in which the land is divided into mountains (47%), plains (22%), deserts (31%), and an arable land area of 1.36 × 10^6 hm^2 (Xie *et al*., 2007). The Tarim River is mainly recharged by alpine glacier and snow melt water and precipitation, totaling 38.2×10^{10} m^3/a (Jiang *et al*., 2007). Due to the impacts of climate change and human activities, only Aksu River, Yarkand River, Hotan River and Kaidu River now supply water to the mainstreams Tarim River (Jiang *et al*., 2007). The Aksu River, Yarkand River and Hotan River join the Tarim River in the upper reaches, while the Kaidu River flows into the Tarim River in the lower reaches. The Tarim River Basin has a typical continental climate because it is far away from the ocean and surrounded by high mountains. It is extremely arid, with poor precipitation and strong potential evaporation (Zuo *et al*., 2006). The Tarim River is about 1,321 km long from the confluence composed of the Aksu, Hotan, and Yarkand rivers to Taitema Lake (Fig. 1).

2 Methods

The annual data of temperature, precipitation and runoff during the period of 1957–2006 were collected from six stations in the headstreams of the Tarim River and two stations on the Tarim River itself (Fig. 1). The Tongguzlok and Uruwat stations are located on the Hotan River, Kaqung station on the Yarkand River, Shrikilank and Xehera stations on the Aksu River and Dashankou station on the Kaidu River. Allar station is located on the mainstream and is the first hydrological station of the Tarim River while Kara station is located on the Tarim River at the junction between the middle and lower reaches. Therefore, this dataset may be regarded adequate to represent the large-scale temperature/precipitation/runoff variations occurring over the Tarim River Basin. The information of the selected stations in the basin is shown in Table 1.

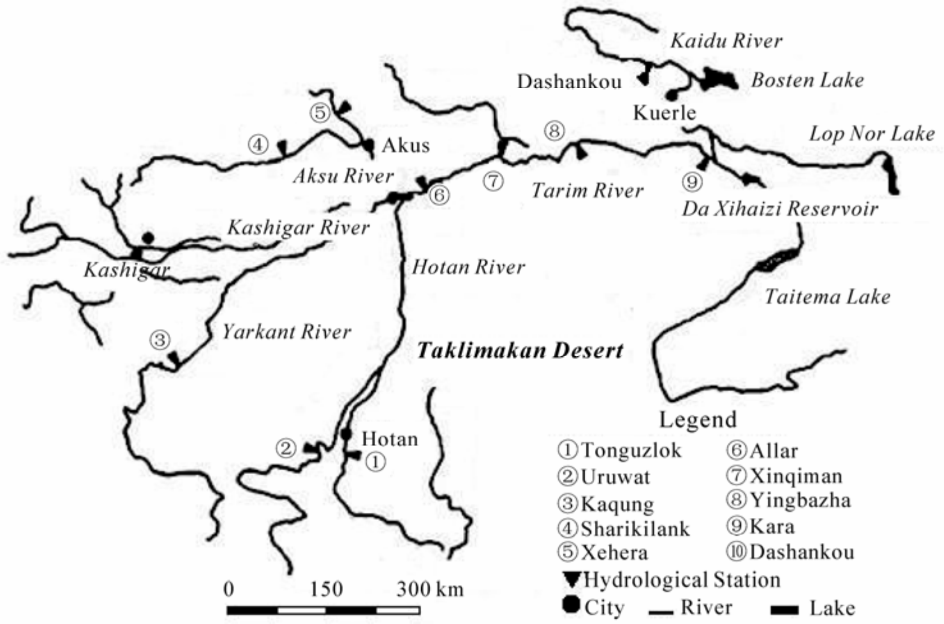

Fig. 1 The sketch map of the Tarim River Basin

Table 1 Main stations of the Tarim River

Station	River system	Altitude (m)	Longitude	Latitude	Period
Tongguzlok	Hotan River	1,650	79°55′	36°49′	1957–2006
Uruwat	Hotan River	1,800	79°26′	36°52′	1957–2006
Kaqung	Yarkant River	1,370	76°54′	37°59′	1957–2006
Sharikilank	Aksu River	2,000	78°36′	40°57′	1957–2006
Xehera	Aksu River	1,487	79°37′	41°34′	1957–2006
Dashankou	Kaidu River	1,340	85°44′	42°13′	1956–2006
Allar	Tarim River	1,012	81°05′	40°50′	1960–2006
Kara	Kashigar River	1,900	75°12′	39°33′	1958–2006

2.1 Partial correlations

Partial correlation analysis is a method to study the linear correlation between two variables whilst they are partially correlated with the linear effect of another variable. Partial correlation coefficient is called the 'first order partial correlation' when the two variables correlate with one further variable. A partial correlation coefficient quantifies the correlation between two variables while they influence one or several other variables. What exactly is the correlation $r_{y1.2}$ between variables x_1 and y conditioning on x_2? It is the correlation between the parts of x_1 and y that are uncorrelated with x_2. To obtain these parts of x_1 and y, they are both regressed on x_2. The residuals of the regression are then the parts of x_1 and y that are uncorrelated with x_2. The correlation between these residuals of x_1 and y is the partial correlation between x_1 and y when conditioning on x_2. $r_{y1.2}$ is a first-order partial correlation coefficient because it is conditioned solely on one variable (x_2) (De La Fuente *et al.*, 2004; Yu *et al.*, 2007).

The linear function of x_2 was controlled when analysis showed partial correlation with and between x_1 and y variables. The first order partial correlation coefficient quality of x_1 and y is defined as:

$$r_{y1,2} = \frac{r_{y1} - r_{y2} r_{12}}{\sqrt{(1 - r_{y2}^2)(1 - r_{12}^2)}}. \tag{1}$$

Where r_{y1}, r_{y2}, r_{12} stand for the correlation coefficient of y and x_1, y and x_2, and x_1 and x_2, respectively. Partial correlation coefficients range from −1 to +1. When r_{y12} is greater than 0, this indicates that there is a positive linear relationship between two variables; when r_{y12} is smaller than 0, this indicates that there is a negative linear correlation between two variables; when $r_{y12} = 1$, this indicates that there is perfect positive correlation; when $r_{y12} = -1$, this indicates perfect negative correlation exists between two variables; when $r_{y12} = 0$, there is no linear relationship between the two variables.

Thus we can use partial correlation coefficients to distinguish between the correlations of two variables due to direct causal relationships from the correlations between the same two variables that originate *via* intermediate variables (sequential pathways) or directly due to other variables (common causes). Although partial correlation analysis still does not infer causal relationships, it excludes many of the possibilities, and thus is a step in the direction of causal inference (Shipley, 2002).

The test statistic for partial correlation analysis is called *t* statistic, and is defined mathematically as:

$$t = r\sqrt{\frac{n-q-2}{1-r^2}} \,. \tag{2}$$

Where, r is the partial correlation coefficient; n is the number of samples; q is the order; n–q–2 is the freedom. The null hypothesis (H_0), this is, the relationship between runoff and temperature/precipitation is not significant correlation, is accepted if the test statistic T is not statistically significant.

2.2 Exponential smoothing

The Holt double exponential smoothing model can be applied to time series data with a trend. Exponential smoothing is a procedure for continually revising a forecast in the light of more recent experience. In other words, recent observations are given relatively more weight in forecasting than the older observations. The trend is a smoothed estimate of average growth at the end of each period (Taylor *et al.*, 2003; James *et al.*, 2004; Prajakta *et al.*, 2004; Baki *et al.*, 2007; Sarah *et al.*, 2010).

Double exponential smoothing applied to time series data, the first smoothing formula is shown as:

$$f_t^{(1)} = ay_t + (1-a)f_{t-1}^{(2)} \,. \tag{3}$$

The second smoothing formula is:

$$f_t^{(2)} = af_t^{(1)} + (1-a)f_{t-1}^{(2)} \,. \tag{4}$$

Where, $f_t^{(1)}$ is an exponential smoothing value; $f_t^{(2)}$ is double exponential smoothing value; The Holt double smoothing is not applied directly to the second exponential smoothing. The original sequence data and the trend series are smoothed, respectively.

The model's general form is:

$$f_{t+m} = S_t + b_t m \,. \tag{5}$$

Where, S_t and $b_t m$ are two parameters in the model.

The specific formula for simple exponential smoothing is:

$$S_t = ay_t + (1-a)(S_{t-1} + b_{t-1}) \,; \tag{6}$$

$$b_t = \gamma(S_T - S_{t-1}) + (1-\gamma)b_{t-1} \,. \tag{7}$$

Where, S_t is smoothed value; b_t is smoothed value for the trend which is the difference between two adjacent smoothed values; γ is the initial parameter for the model.

2.3 Autoregressive Integrated Moving Average Model modeling in time series analysis

The time series data of the Allar station during the period of 1957–2007 were used as the forecast. The basic idea of the Autoregressive Integrated Moving Average Model (ARIMA) is to use the time series of past values and present values of the linear combination to predict its future values (Yin *et al.*, 2010). This model-building process is designed to take advantage of associations in the sequentially lagged relationships that usually exist in data collected periodically.

The transformed series were different at the mean, and corrected to induce stationarity. Sample autocorrelation and partial autocorrelation functions were used to identify the ARIMA model of the appropriate order. Estimates of the model's parameters were obtained by the maximum likelihood method. Diagnostic checking included residual analysis and the Akaike Information Criterion (Yin *et al.*, 2010) was used to compare goodness-of-fit among ARIMA models. The final model was a result of several iterations of the identification, estimation, and checking process, and met the conventional criteria for the adequacy of the model (Mohammad *et al.*, 2006; Saeed *et al.*, 2009; Yin *et al.*, 2010).

The basic processes of ARIMA modeling are: (1) Smoothing the data series; (2) Calculating the autocorrelation and partial correlation coefficients to assess pretreatment ARMA modeling data requirements; (3) Identifying ARIMA model (according to the truncation of autocorrelation (AC) and partial correlation coefficients (PAC), the type of model could be identified); (4) Estimating the parameter and testing the fit of the ARIMA model; and (5) Predicting future trends using the ARIMA model.

3 Results and discussion

3.1 Trend of temperature, precipitation and runoff time series

In the past 50 years, the temperature of the Tarim River Basin shows a trend of continuous increase, especially in the four headstreams of the Tarim River (Fig. 2). The average annual temperatures of the Aksu River, Hotan River, Yarkant River and Kaidu River had the increasing trends of 0.27ºC/10a, 0.31ºC/10a, 0.04ºC/10a, and 0.18ºC/10a, respectively. The average annual temperature of the Hotan River showed a clearly, monotonously increasing trend. In the 1990s, the Kaidu River had a large increase in temperature, while there was a significant drop in average temperature in Yarkand River. The increase in temperature resulted in a significant increase in runoff. In the 1960s, there were serious droughts in the basin (Wang *et al.*, 1996). In the mid 1970s to 1980s, there was a conversion period, and the situation of drought and flood was more serious. Since the late 1980s, drought appeared to be decreased and floods increased. Since the mid 1990s, the situation of downstream was quite different from the rests of the basin (Su *et al.*, 2007).

In the past 50 years, the precipitation at every section of the Tarim River Basin has increased (Fig. 3). The annual precipitations of Aksu, Hotan, Yarkant and Kaidu rivers had the increasing trends of 12.5 mm/10a, 4.5 mm/10a, 11.2 mm/10a, and 8.0 mm/10a, respectively. According to the data for Hotan and Yarkand rivers, the years of positive above average values are roughly the same as those for negative below average values, while on the Aksu and Kaidu rivers, the years of positive values became more common after 1987. The values of the linear trends of the Aksu, Hotan, Yarkand and Kaidu fivers were 2.19, 0.29, 0.56, and 1.05, respectively. Increased evaporation rates resulted in reductions in river runoff. However, this was more than balanced by the increased rates of precipitation, and so, overall, river runoff increased.

In the past 50 years, the Aksu, Yarkant and Kaidu rivers have exhibited the increasing trends in annual runoff. The streamflow in the Aksu River showed a significantly, monotonously increasing trend at a slope of 0.74. However, there has been a subtle reduction in runoff in the Hotan River, at a slope of –0.42 (Fig. 4). Particularly in the 1990s, wet-years appeared to be more common and the natural runoff from mountains also shown an upward trend. The 1990s was an important abrupt point of climate change when the

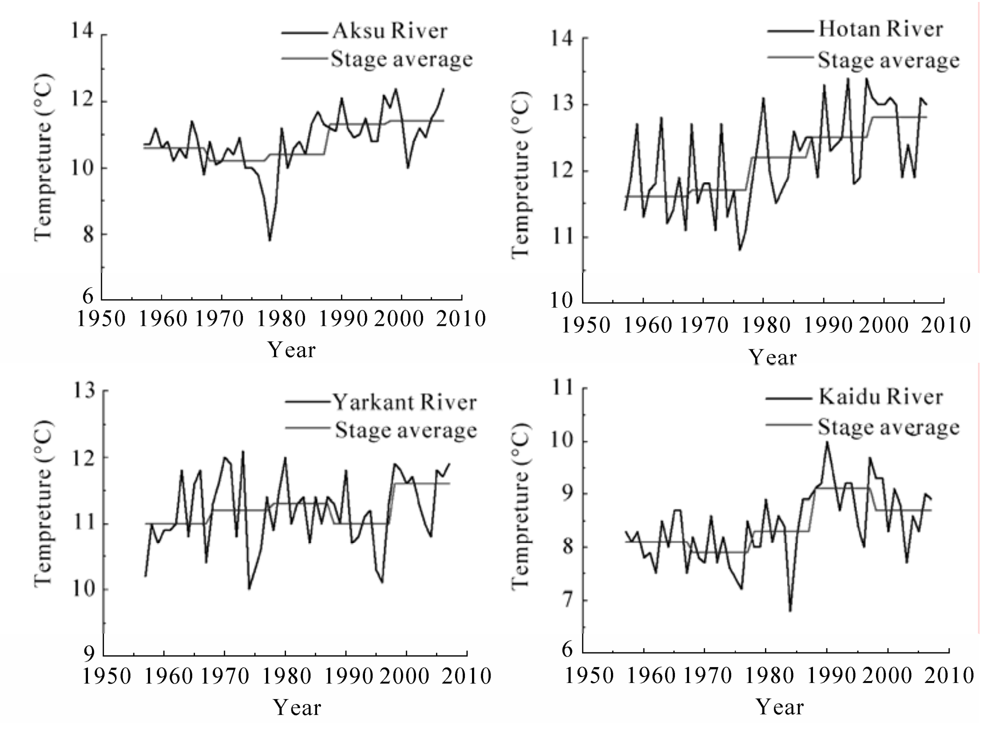

Fig. 2 Average annual temperature in four major headstreams of the Tarim River

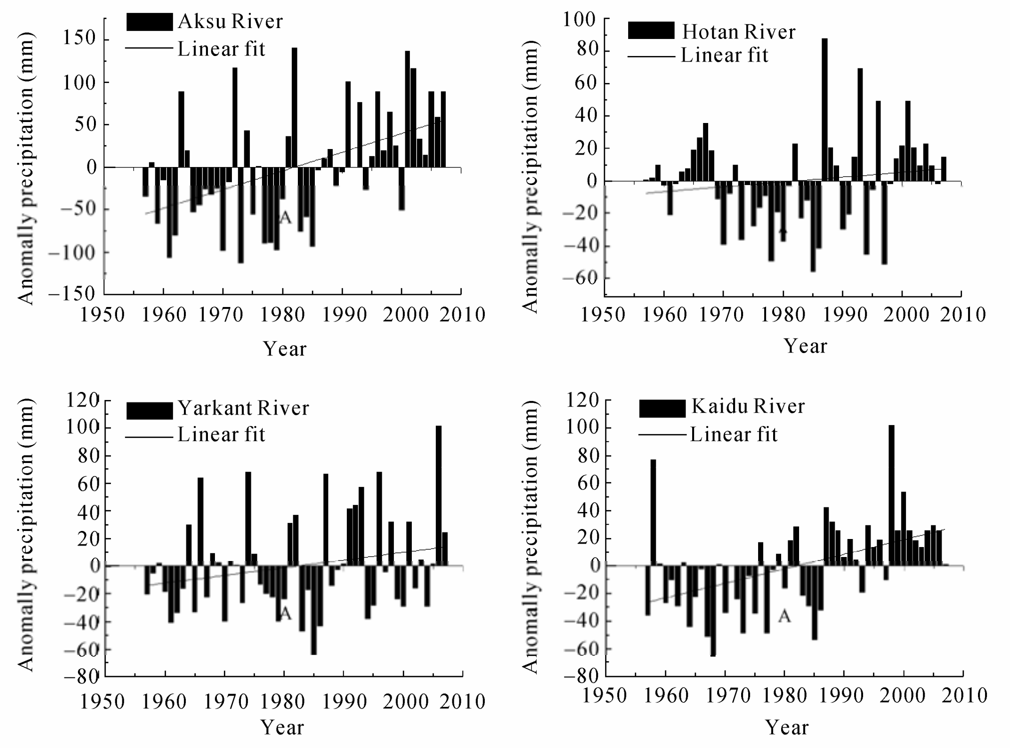

Fig. 3 Annual anomaly precipitation in four major headstreams of the Tarim River

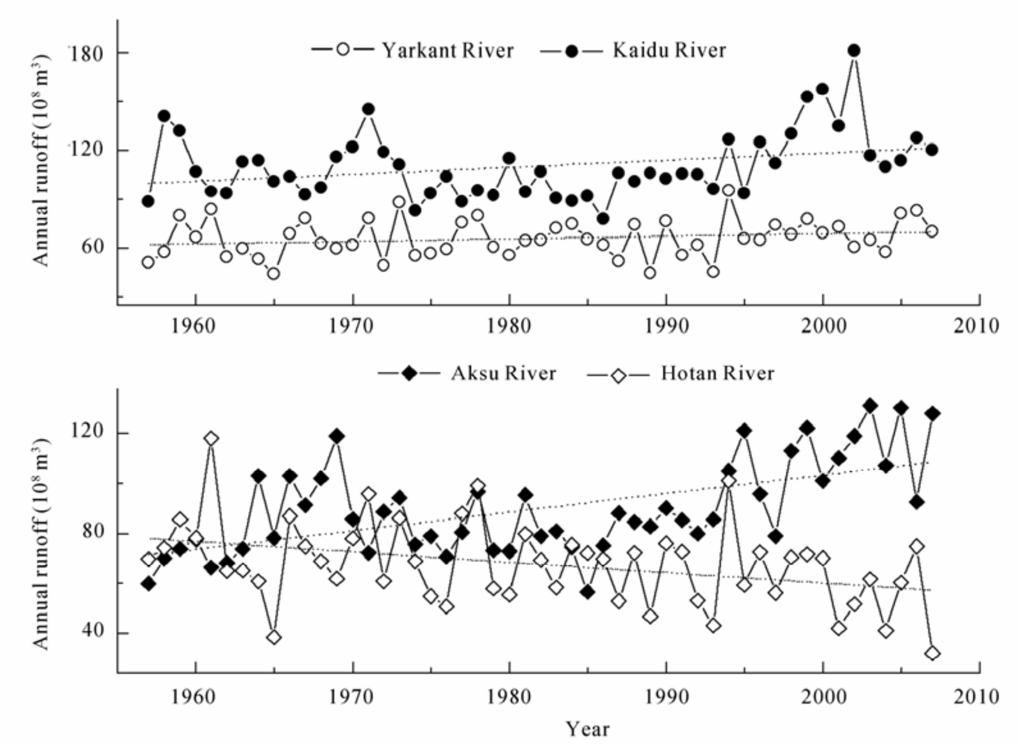

Fig. 4 Annual anomaly runoff in four major headstreams of the Tarim River

temperature showed a significant increase and the river runoff increased. As a headstream of the Tarim River, the decrease of runoff in the Hotan River due to decreased glacier melting is larger than that in the Kaidu River during the 1970s–1980s due to the decreased precipitation (Xu *et al.*, 2006). On the other hand, the increase in glacier melt water in the 1990's produced an increasing rate of runoff greater than the rate of increase from precipitation. In the past 50 years, the Aksu River has shown a trend of increasing runoff, and an increased possibility of flooding in summer. This may be related to the geographic distribution of the headstreams. Those rivers that mainly relied on the supply of glacier melt water have shown an increasing trend in annual runoff when temperature increased. However, water flow in the mainstream has been declining when compared to the rising flow rates in the headstreams. From the 1950s to 2006, water flowing into the Tarim River from the four headstreams reduced by 1,514 × 10^8 m^3/a (Duan *et al.*, 2009).

3.2 Partial correlation analysis between runoff, temperature and precipitation

Table 2 shows the partial correlation analysis for taking precipitation/temperature as a control variable. Firstly, the associated analyses were carried out on the four headstreams' average annual runoff, average annual temperature and average annual precipitation, and then we took the average annual temperature or precipitation as a control variable to do partial correlation analysis.

Table 2 The partial correlation analysis between runoff and temperature and precipitation of the four headstreams

Item	Aksu River	Hotan River	Yarkant River	Kaidu River
P	0.410^{**}	-0.393^{**}	−0.147	0.515^{***}
T	0.230	−0.079	0.276^{*}	0.255
P (Control T)	0.369^{**}	-0.398^{**}	None	0.468^{***}
T (Control P)	None	None	0.266	None

Note: *, ** and *** indicate the significance at the levels of $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

The correlation between average annual runoff and average annual precipitation is significant for the Aksu River, and highly significant for the Kaidu River, but for the Hotan River, it is negatively significant. Because the partial correlation coefficients of the three headstreams (Aksu River, Hotan River and Kaidu River) have no significant differences, the hypothesis that the correlation between average annual runoff and average annual precipitation is significant has to be rejected. The correlation between average annual runoff and average annual temperature for the Yarkand River is significant, however, the result of partial correlation coefficient of the two populations had no significant differences. And the null hypothesis is not rejected, so the correlation between average annual runoff and average annual temperature is not significant.

In conclusion, the changes in temperature and precipitation had great impact on runoff in the four headstreams, in which the precipitation had a large positive impact on the Aksu River and the Kaidu River, a negative impact on the Hotan River, but temperature had a positive influence on the Yarkand River, whereas the changes in temperature had a very weak linear effect on the Hotan River runoff. The changing of the surface runoff originated from climate change. The special hydrological characteristics of the arid zone determine the significant associations between streamflow and the two climatic factors, precipitation and temperature.

3.3 Holt Double Exponential Smoothing Model fitting between runoff and temperature or precipitation

The Holt Double Exponential Smoothing Model was used to fit the two variables (runoff and temperature/precipitation), which is equivalent to linear regression analysis. Table 3 shows the fit for average annual runoff and average annual temperature/precipitation of three of the headstreams (Aksu River, Hotan River and Yarkand River) of the Tarim River, following Holt Double Exponential Smoothing. The multiple correlation coefficients for the Aksu River, Hotan River and Yarkand River indicate that there was a strong connection between the independent variable and the dependent variable (Fig. 4). The Kaidu River had no condition to do exponential smoothing, and runoff had no strong connection with temperature/precipitation when trend fitting. It implies that the fit between the independent variable and the dependent variable was relatively close. A significant negative correlation between runoff and temperature was shown for only the Hotan River, while significant positive correlations were shown between precipitation and runoff for the Aksu and Yarkand rivers. Temperature affects glacier melt and accumulation of melt water, and elevated temperatures result in strong repercussions for extensive glacier melting (Jiang *et al.*, 2007). As precipitation increased, runoff increased in the rivers which had a small proportion of glacier melting, and runoff reduced in the rivers which had a major proportion of glacier melting.

3.4 Trend analysis of the runoff in the main Tarim River stream

The parameters' estimates and five forecast values for the optimum ARIMA (0, 1, 1) are shown in Table 4. There were 48 observations used to make the forecast, and only one observation was eliminated by difference. The autocorrelation and partial autocorrelation functions of the residuals showed good-fit (Fig. 5).

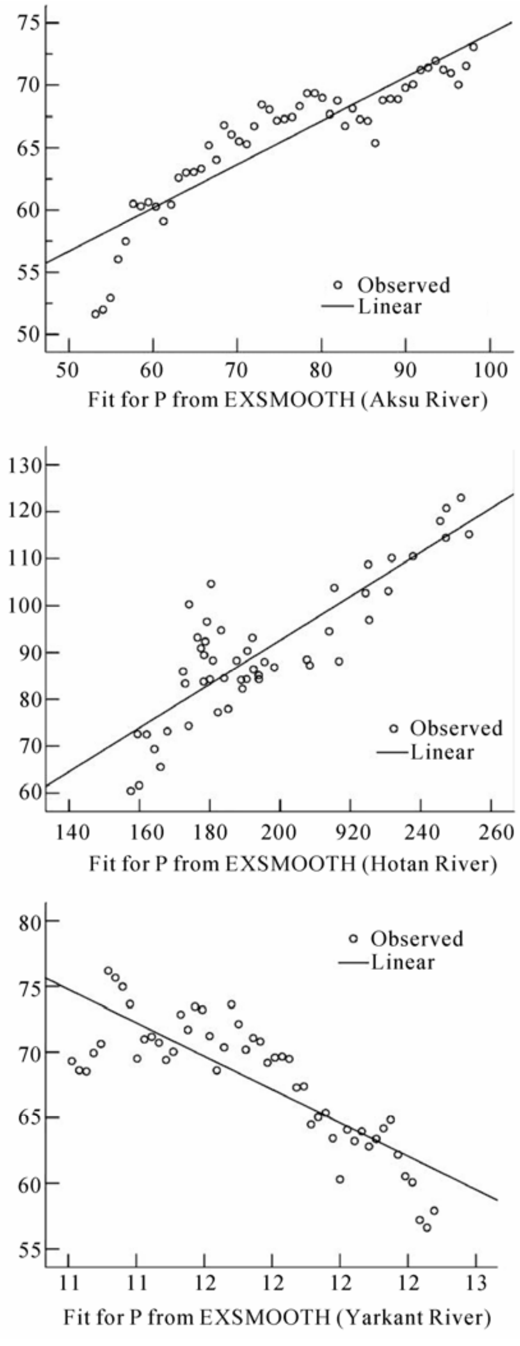

Fig.5 Trends fitting between runoff and temperature or precipitation of three head streams

The goodness of fit test of the optimum ARIMA (0, 1, 1) model showed non-significant autocorrelations in the residuals of the model. The estimate value is high enough to be strongly significant, indicating that ARIMA (0, 1, 1) fits the data well and is suitable for accurate forecasting (Table 4). Drawing the curve of the data revealed overall changes to runoff in the main river. Streamflow at Allar station, the first hydrological gauging station in the mainstream, displayed a decreasing trend, and the trend is statistically significant ($P < 0.05$) (Fig. 6), while annual streamflow in the headwater catchments exhibited an increasing trend (Chen *et al.*, 2008). The results of the temperature analysis showed that increases in air temperature had resulted in the increasing of streamflow in the Tarim River during the last 50 years. It may result in the decrease of runoff in the plain area due to an increase in evaporation. However, the negative trends in streamflow in the Tarim River have mainly resulted from anthropogenic activities. The potential impact of climate on the study area is relatively slow compared to the impacts caused by human activity. In order to deal with the issue of decreasing downstream water supplies caused by human activities and their impact on

Table 3 Holt Double Exponential Smoothing fitting between runoff and temperature or precipitation of three headstreams

Aksu River	Model	Parameter estimation	
Equation	R Square	Constant	b1
Linear	0.729^{***}	–1.028	0.468
Hotan River	Model	Parameter estimation	
Equation	R Square	Constant	b1
Linear	0.688^{***}	171.354	–8.472
Yarkant River	Model	Parameter estimates	
Equation	R Square	Constant	b1
Linear	0.804^{***}	39.233	0.349

Note: *** indicates the significance at the level of $P<0.001$.

Table 4 Autoregressive integrated moving average model (0, 1, 1) of the Allar station

Parameters		Estimating	Standard error	t-ratio
Autoregressive parameter		1.00	0.07	13.10
Observation	Forecast	Std. error	Confidence limits of 95%	
1	42.0405	10.2101	22.0289	62.0520
2	41.9117	10.2101	21.9002	61.9232
3	41.7829	10.2101	21.7714	61.7944
4	41.6542	10.2101	21.6426	61.6657
5	41.5254	10.2101	21.5139	61.5369

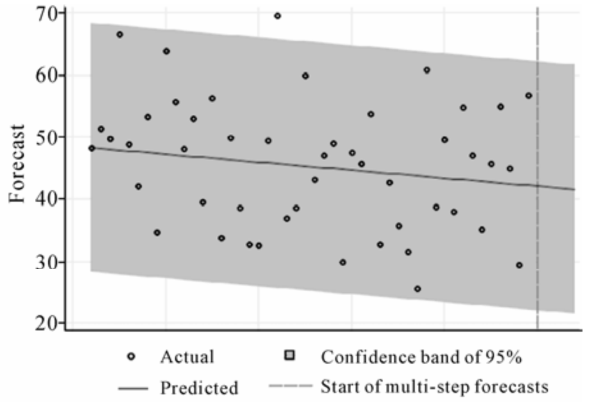

Fig. 6 Forecasts values (10^8 m^3) of the runoff at Allar station for the final ARIMA (0, 1, 1) in Tarim River during the period of 1957–2007

deterioration of the ecological environment, we should develop ecological water assurance and watersheds vegetation protection. It is necessary to establish effective water resource management and control mechanisms throughout the basin (Xie *et al*., 2007). It should be implemented through rational allocation of water resources in the upstream rivers and upper and middle reaches of the Tarim River, along with a corresponding increase in the promotion of water recycling and reutilization in agriculture, industry, and daily life.

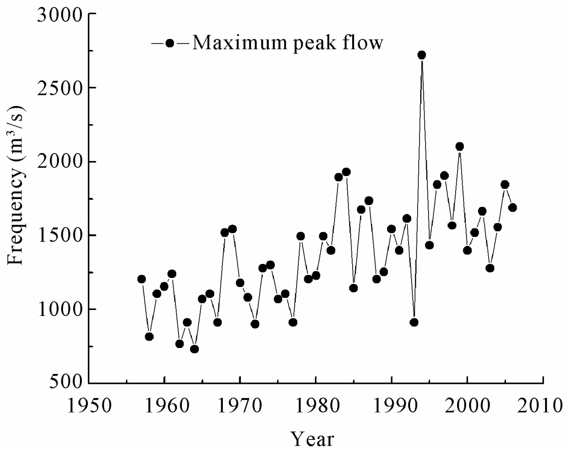

Fig. 7 The peak discharge variation at Xehera station during the period of 1957–2006

If the temperature continues to rise, the snow-line will retreat upslope, and glaciers will shrink, and the thaw area will increase, and the snow and ice accumulation area will decrease. Due to the significant increase of surface temperature, runoff from glacier melting is likely to increase significantly in future, increasing the risk of flooding in the headstream and further downstream. Some relative researches show that the glaciers whose areas are less than 1 km^2 will completely melt in 50 years (Ding, 2010). In the upper reaches of the Tarim River, where flow mainly relies on the supply of glacier melt water, a short-term increase in glacier melt would regulate the river runoff. When precipitation is inadequate to replenish and replace the glaciers' melt water, the degradation of glaciers will inevitably affect the environment and human habitat in the future (Xu *et al*., 2006). On the Aksu River, the largest one of the headstreams of the Tarim River, glacier melt water flows are changing as glaciers retreat, and peak runoff volume is increasing. Figure 6 shows the variation in peak discharge each year at Xehera station in 1957–2006. Xehera station is located on the Aksu River, with a natural hydraulic linkage to the mainstream of the Tarim River, and located in the mountains where anthropogenic disturbance is negligible. The data in Fig. 6 shows that the maximum peak flow each year has followed an increasing trend during the past 50 years, reaching to 2,720 m^3/s in 1994. The Tarim River Basin has warmed since the late 1970's (Fig. 2), and this in turn has affected the distribution of the basin's glaciers, frozen soil and snow, with significant impacts on the region's agricultural production and people's lives. Peak flows for melt water carry a high frequency than peak flows for rainfall in middle zone of mountains. Peak flows for melt water is closely related to rising temperature and melting glaciers in high mountains, and it always happens in summer. In the past 20 years, the increased runoff in mountains has some connection with the increased temperature under the background of global climate change (Chen and Xu, 2005). In addition, sudden floods often occur in the Yarkant River and the Aksu River. It may result from glacial barrier lakes releasing flood suddenly. The rate of sudden floods for melt water has an increasing tendency in the Tarim River Basin (Chen *et al*., 2010). In order to deal with the problem that temperatures continue rising, leading to increased glacier melting, a flood prevention and water use plan should be drawn up to reduce flooding risk and take advantage of the additional water in the peak flows. Flood control installations should be built in flood-prone areas as early as possible, while estimates of the amount of additional water resources from accelerated glacier melting should be calculated as soon as possible (Chen *et al.*, 2004).

4 Conclusions

Our results reveal that the headwaters of the Tarim River Basin have become warmer and wetter in the last 50 years. The annual runoff exhibited a significant correlation with the temperature and precipitation in the four major headstreams. Precipitation had a greater positive impact on flow rates in the Aksu, Hotan and Kaidu rivers, but temperature had the larger positive impact on the flow in the Yarkand River.

The R value for the multiple correlation model of the three origins indicates a close fit between the independent variable and the dependent variable. A significant negative correlation was shown only between runoff and temperature for the Hotan River, and a significant positive correlation was shown between precipitation and runoff for the Aksu and the Yarkand rivers. The model is statistically significant.

Annual streamflow for the Allar station represents overall changes and annual fluctuations in the headstream flows into the Tarim River. Analysis of annual streamflow data for the period of 1957–2007 showed that the runoff (streamflow) flowing through Allar station displayed a significant decreasing trend.

Acknowledgements

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