Impacts of climate change on headstream runoff in the Tarim River Basin

Hailiang Xu, Bin Zhou and Yudong Song

ABSTRACT

The impacts of climate change on annual runoff were analyzed using hydrologic and meteorological data collected by 8 meteorological stations and 15 hydrological stations in the headstream of the Tarim River Watershed from 1957 to 2005. The long-term trend of climate change and hydrological variations were determined by parametric and non-parametric tests. The results show that the increasing scale of precipitation is less than the scale of rising temperature. The change and response of hydrological process have their own spatial characteristics in the tributaries of a headstream. Precipitation and temperature do not increase simultaneously in the hydro- and meteo-stations located in the headstream. The temperature and runoff displayed certain relations, and a relationship also existed between precipitation and runoff. The annual runoff of the Aksu and Kaidu rivers was consistent with an increasing trend in temperature and precipitation during the past 50 years; temperature increases have a greater effect on annual runoff. These results suggest that with the increase of temperature in the Tarim River Watershed, the glacier in the headstreams would melt gradually which results in runoff increase in several headstreams. However, glacier meltwater would be exhausted due to continual glacier shrinkage, and the increased trend of runoff in the headstreams would also slow or lessen. Thus, regional water resources shortage problems are still serious and have become a major feature in the Tarim River Watershed.

Key words | glacier melting, precipitation, runoff, Tarim River Watershed, temperature, water resources

Hailiang Xu
Bin Zhou (corresponding author)
Yudong Song
Xinjiang Institute of Ecology and Geography,
Chinese Academy of Sciences,
Urumqi, 830011,
China

Bin Zhou (corresponding author)
College of Resources and Environment,
Xinjiang University,
Urumqi, 830046,
China
E-mail: *Zhoubin@ms.xjb.ac.cn*

INTRODUCTION

Global climate models have demonstrated significant impacts on local and regional hydrological regimes (Arnell 1999, Gleick 1999, Arora & Boer 2001, Bouraoui *et al.* 2004). Climate change may increase precipitation and evapotranspiration, which will enhance the hydrological cycle. Under these scenarios, glacier melt would shift the snowline upwards, affecting discharge rates and timing (Foster 2001, IPCC 1997, Meybeck 2004). With the acceleration of the scientific response to global climate change in recent years, numerous studies are now available which document the sensitivity of streamflow to predicted climate change for river basins on a global scale (Houghton *et al.* 2001).

The Tarim River is the largest internal river in China, which had an estimated natural flow of 800–900 × 10^6 m^3 per annum from snow and glacial-fed sources (Hou *et al.* 2006). The total contribution of mountainous areas to catchment discharge may represent as much as 95% of the total flow (Liniger *et al.* 1998). The Tarim River basin represents a closed catchment with several tributaries draining into it; these are the Hetian, Yarkand and Akesu Rivers (Figure 1).

The Tarim River is exceptional as an arid inland watershed and a closed catchment. Its changes in regional hydrology have particular characteristics compared to other areas in the mid and high latitudes of the northern hemisphere.

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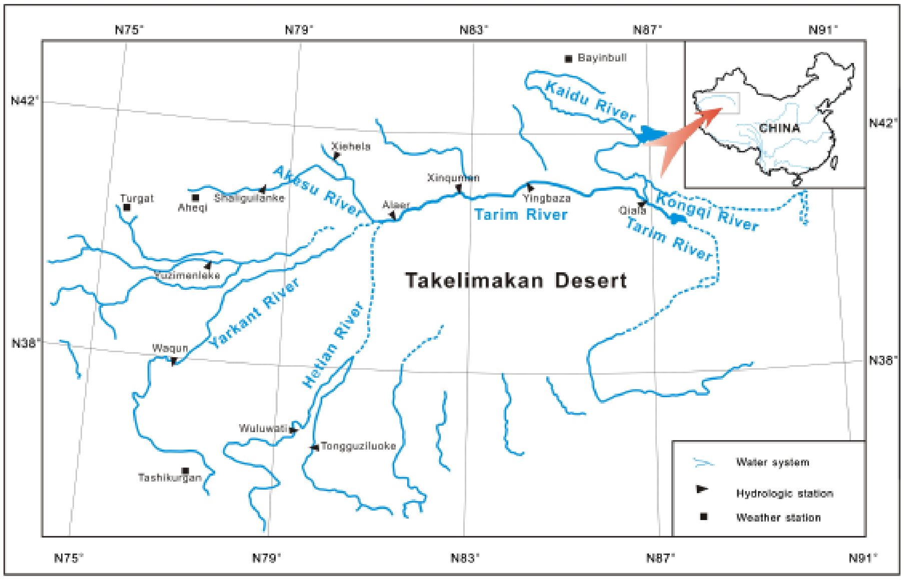

Figure 1 | Map of Tarim River watershed.

The existence of an oasis is entirely dependent upon the runoff from thawed glaciers and snow as well as mountain orographic rainfall. Glacier meltwater, rainfall and snowmelt and base flow represent 48.2%, 27.4% and 24.4% of total flow, respectively (Wang 1998, Tang 2001, Wu *et al.* 2003). Climate change on a geological scale would lead to a variation of runoff (Song 1999, Lei *et al.* 2003; Xu *et al.* 2003; Zhang *et al.* 2003).

The climate of the Tarim Basin has tended towards hyperaridity since the late Pleistocene. It is claimed that a climatic shift from a cold-drying pattern to the warm-wetting pattern of northwest China started in the 20th century (Shi *et al.* 2002; Wang *et al.* 2003; Yang & Shi 2004). Detecting plausible long-term climate change from hydrological processes is potentially the first step in understanding and managing the vulnerability of water resources. Some research has demonstrated that precipitation exerts an overwhelming influence on annual runoff (Schaake 1990, Nash & Gleick 1991, Jeton *et al.* 1996). It is reasonable to consider recent climatic variability, in particular long-term series of meteorological variables in regions with different hydrologic conditions, in order to assess what effect climatic variations have on runoff variability. It is therefore important to analyze the relationship between climate and runoff in the headstream of the Tarim River Watershed.

This paper discusses the impact of climate change on runoff in the headstream of the Tarim River. We aim to determine the sensitivity of runoff to climate shifts and analyze the connections in temperature, precipitation and runoff in observed climatic and hydrological data. We first present observed streamflow trends. Selected precipitation and temperature trends are then presented and linked to changes in runoff. A correlation analysis between watershed attributes and observed streamflow trends is presented with a focus on mountaining basins and plains.

METHODS

Study area

The Tarim River Basin covers the entire south Xinjiang Province of western China, an area of approximately 1020 × 103 km^2. The region is characterized by both rich natural resources and a fragile environment (Figure 1). The watershed lies in a warm-temperate arid desert climate and the climate is typically continental. The annual precipitation varies between 30 and 60 mm, with a progressive increase in precipitation from the southern plain to mountains. Evaporation ranges from 2000 to 3000 mm per year.

The Tarim River is a dissipative inland river which is entirely supplied by its headstreams rising in the mountainous regions. Its ecosystems include alpine glacier zones, cold-humid alpine meadow zones, humid mid-mountain forest zones, semi-arid hill shrub-herb vegetation zones and arid plain desert oasis.

Data description

The collected data include the hydrological data from 15 hydrological stations at the 7 headstreams of the Tarim River during the period 1957–2005. The meteorological data were collected from 8 meteorological stations distributed over the mountainous regions and plains during the period 1961–2005 (Tables 1 and 2).

Analysis methods

Non-parametric statistics are often favoured for the detection of historic streamflow trends due to the potential lack of normality of their distribution. Trend analyses in this study were conducted by the non-parametric Kendall test, widely used in hydrological studies (Kendall 1975, Van & Hughes 1984, Pei *et al.* 1999). The data were analyzed for trends using Kendall's sequence correlation test. The correlations among temperature, precipitation and runoff in the headstreams were analyzed using the harmonious coefficient *W* test and two-variable Wilcoxon test. To test the trend consistency, the chi-square tests and Durbin-Watson tests were used. For the statistical tests we used SPSS (Statistical Program for Social Sciences) version 11.0 (SPSS Inc., Chicago IL).

Table 1 | Meteorological stations in the headstream areas of the Tarim River watershed

Area	Watershed	Meteorological station	Latitude	Longitude	Elevation (m a.s.l.)	Observation time (year)
Mountainous region	Yarkant River	Taxkorgan	37.47°N	75.14°E	3094	44
	Kaxgar River	Turgart	40.31°N	75.24°E	3507	44
	Aksu River	Akqi	40.93°N	78.45°E	1986	44
	Kaidu River	Bayanbuluk	43.03°N	84.15°E	2459	44
Plain	Hetain River	Hetain	37.13°N	79.93°E	1375	44
	Kaxgar River	Kashgar	39.28°N	75.59°E	1291	44
	Aksu River	Aksu	41.10°N	80.14°E	1105	44
	Kongque River	Korla	41.12°N	86.08°E	932	44

Table 2 | Hydrological stations in the mainstream of the Tarim River watershed

River	River rising mountain	River name	Hydrologic station	Observation period	Observation time (year)
Hetain River	North slope of Kunlun Mt.	Karakax River	Tongguzlok	1957–2005	49
		Yurungkax River	Uruwat	1957–2005	
Aksu River	South slope of Tianshan Mt.	Kunmarik River	Xehera	1957–2005	49
		Toxkan River	Sharikilank	1957–2005	
Yarkant River	Karakorum Mt.	Yarkant River	Kaqung	1957–2005	49
			Yuzmenlek	1974–2005	32
Kaidu-Kongque River	South slope of Tianshan Mt.	Kaidu River	Dashankou	1956–2005	49
		Kongque River	Taxdian	1982–2005	24

Kendall sequence correlation test

The changing trends of the annual runoff series of the three main headstreams and mainstream of the Tarim River were first tested and analyzed. The number P_i of $X_i < X_j$ in the observed values $(X_i, X_j; j > i)$ for the annual runoff series $X_1, X_2, X_3, \ldots, X_n$, and the subsets of the sequence (i, j) are $(i = 1, j = 2, 3, 4, \ldots, n)$, $(i = 2, j = 3, 4, 5, \ldots, n)$ and $(i = n-i, j = n)$. The statistical value related to the test is

$$Z_c = \frac{T}{\sqrt{\mathrm{var}(T)}} \tag{1}$$

where

$$\mathrm{var}(T) = \frac{2(2n+5)}{9n(n-1)} \tag{2}$$

and

$$T = \frac{4\sum Pi}{n(n-1)} - 1. \tag{3}$$

The statistical value T can be derived from the annual runoff series by using Equation (1) (Helsel & Hirsch 1992).

Kendall's harmonious coefficient *W*

Kendall's W test appraises the sequence of the values of n variables or k series, and determines the correlation between them and the coefficient W. The result is dependent upon whether there are similarities between the two variables or not. a is the significant level for the test. When $a \leq 0.05$, the changes of two variables are remarkably synchronous, there are significant correlations. When $a \geq 0.05$, the changes of two variables are not synchronous (Birsan *et al.* 2005). The equation of Kendall's harmonious coefficient W is given as

$$W = \frac{\sum_{j=1}^{n} \{R_j - [m(n+1)]\}^2}{m^2 n(n^2-1)/12}. \tag{4}$$

Wilcoxon's two-variable correlation test

Although it is useful to test the correlation degree between hydrological process and meteorological factors with Kendall's harmonious coefficient W, we also use Wilcoxon's non-parametric statistical test to reveal the relationship between hydrological process and different meteorological factors (Hamid & Heigang 2000). The equation of Wilcoxon test is defined as:

$$Z_W = \frac{w - E(w)}{\sqrt{\mathrm{var}(W)}} \tag{5}$$

where

$$W = \sum_{i=1}^{n} \mathrm{rank}(\mathrm{temp}_i); \quad E(w) = \frac{n(n+m+1)}{2};$$

$$\mathrm{var}(W) = \frac{mn(n+m+1)}{12} \tag{6}$$

where n is the number of drought years or wet years and m is the number of neutral years. The hydrological variable is ranked separately for drought and neutral or wet and neutral conditions, these can be divided by Wilcoxon's two-sample sum statistic. The criteria for drought years, wet years and neutral years were distinguished by annual runoff.

RESULTS AND DISSCUSION

Annual runoff trends

The results demonstrate increasing trends in annual runoff in the Tarim River watershed for study periods (Figure 2). Examing the change trend of annual runoff (Table 3), the annual runoff volume at Tongguzlok Hydrological Station on the Karakax River and Uruwat Hydrological Station on the Yurungkax River are increased slightly. However, this trend is not so significant ($Z_c > -1.96$). The annual runoff volume of three other stations has increased (Table 3). At the same time, the annual discharge in the Kaidu and Aksu rivers have also increased. The change in annual runoff volume during the period 1957–2005 using 6 stations has increased greatly since the 1990 s. During the period 1994–2005, the average annual runoff of the headstream was about 3300×10^6 m^3. This is higher than the average runoff during the period 1957–2005, which reveals that the headstream of the Tarim River has been affected by global climate change. These changes have important repercussions for water sources which are extremely low in this area. An increase in the annual runoff from the several headstreams provides potential water

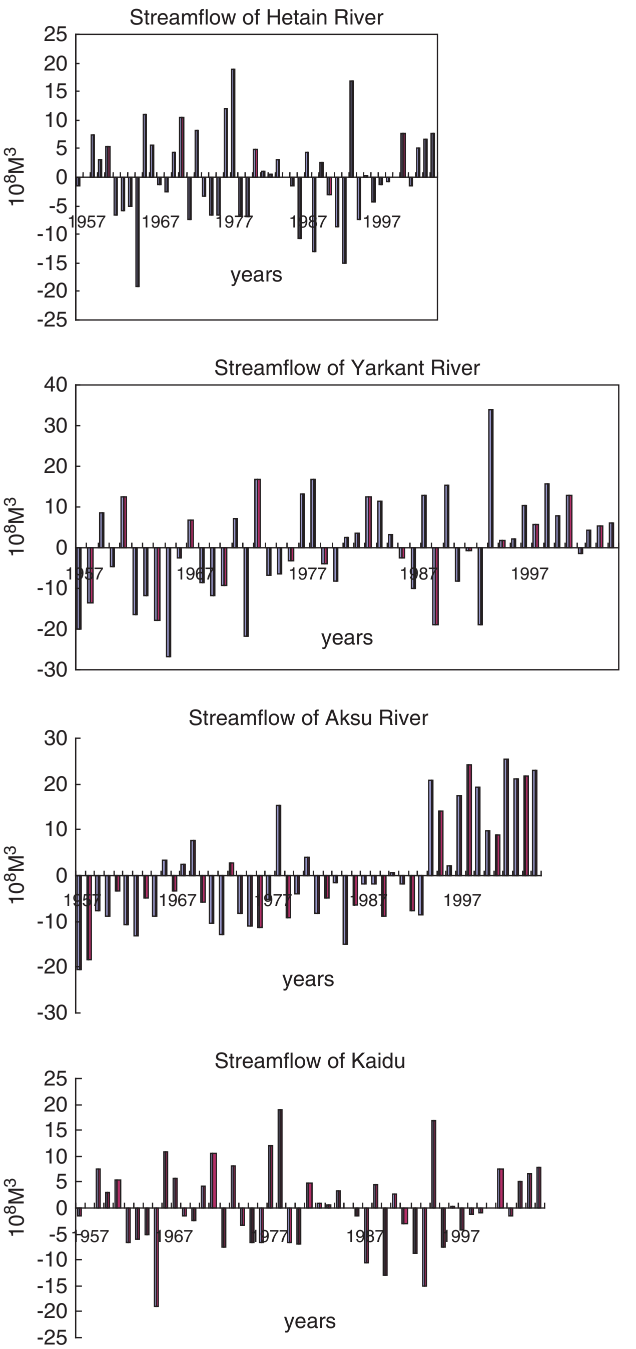

Figure 2 | Variation in annual runoff in the headstreams of Tarim River basin (1957–2005).

sources for meeting water demands in middle and downstream, especially the runoff increase from Kaidu River provides an important water source to the lower reaches of the Tarim River for ecological conservation purposes (Hao *et al.* 2006).

Precipitation and temperature trends

The trends of changing temperature and precipitation have been calculated at the main meteorological stations in the mountainous regions and plains of the headstream areas (Tables 4 and 5). These data show that the precipitation at all 8 meteorological stations is increasing (Table 4), but the trend cannot be confirmed by the statistical results. However, the temperature has increased more than the precipitation, the trend is increasing and the level of significance is $\alpha = 0.05$ (Table 5). When the temperature and precipitation are all increased or decreased from the mountains to plains, we regard these changes as synchronous, which have the harmonious characteristics. From the synchronous temperature and precipitation in the whole drainage basin, the change of temperature is more synchronous from the mountainous regions to plains than precipitation at each station (Tables 6 and 7), because the changes of precipitation in mountains are different from that of plains, but the change of temperature in the whole drainage basin is synchronous. This indicated that temperature increases can be seen across the whole watershed, but precipitation increases are restricted to individual regions.

Relationships between annual runoff, precipitation and temperature

Analysis of the temporal series and the linear increase in both temperature and precipitation in the headstream areas indicates that there is a possibility of the volume of water resources increasing because of climate variability in the headstream areas. We used a non-parametric test to check the relation between temperature and annual runoff and between precipitation and annual runoff at the flow of the main headstreams of the Tarim River.

The situation referred to as H_0 implies there is a correlation between the variation of precipitation (or temperature) and annual runoff; H_1 implies there is no correlation. The annual runoff of the Hetain, Aksu and Yarkant rivers and the precipitation and air temperature in the mountainous regions are tested separately (Table 8). Table 8 shows that the assumption of H_0 cannot be ruled out because the Z_w values are not significant, i.e. there is a correlation between the annual runoff volume of the three rivers and the annual

Table 3 | Changing trend and non-parametric test of annual runoff volume

Hydrological station	**Annual runoff volume (10^8 m^3)**	**Standard deviation**	**Partial coefficient**	**Trend item**	**Trend**	**Z_c**	**Significant test result (0.05)**
Tongguzlok	22.270	4.871	–0.442	−0.0456t + 23.365	Increased slightly	−0.5777	Refused
Uruwat	21.387	4.091	0.113	−0.0211t + 21.894	Increased slightly	−0.871	Refused
Xehera	48.675	7.691	−0.057	0.3478t + 40.327	Increased	4.411	Accepted
Sharikilank	27.675	5.414	0.375	0.2032t + 22.798	Increased	3.824	Accepted
Kaqung	65.430	11.448	0.344	0.1116t + 62.75	Increased	1.201	Refused
Dashankou	51.248	6.787	−0.056	0.5x + 19.079	Increased slightly	3.503	Accepted

Table 4 | Changing trend and non-parametric test of precipitation (R: rejected; A: accepted; $\alpha = 0.05$)

Meteorological stations	**Mean (mm)**	**Standard deviation**	**Coefficient of skewness**	**Trend item**	**Z_c**	**H_0**
Tashkergan	70.036	23.447	−0.582	0.2634t + 64.373	0.726	R
Tuergate	241.174	60.386	0.566	0.9877t + 219.94	0.899	R
Aheqi	206.664	73.726	0.656	2.1677t + 160.06	2.438	A
Bayinbulker	276.402	56.540	1.450	0.3936t + 267.94	0.163	R
Hetain	56.068	32.933	0.941	0.2477t–434.51	0.1165	R
Kashi	54.728	34.114	0.548	0.8659t–1660.1	1.5845	R
Aksu	58.521	29.330	0.961	1.0762t–2073.0	2.5399	A
Kuerle	76.583	30.88	0.100	0.9148t–1735.2	2.2836	A

Table 5 | Changing trend and non-parametric test of temperature

Meteorological stations	**Mean (°C)**	**Standard deviation**	**Coefficient of skewness**	**Item of trend**	**Z_c**	**H_0**
Tashkergan	3.6	0.933	−0.442	0.0275t + 2.954	2.169	A
Tuergate	−3.4	0.639	0.113	0.0298t–4.037	2.415	A
Aheqi	6.4	0.571	−0.057	0.0205t + 5.9755	2.328	A
Bayinbulker	−4.5	1.003	0.375	0.006t–4.6664	0.214	R
Hetain	11.568	0.633	0.344	0.0266t + 11.023	2.2137	A
Kashi	11.955	0.527	−0.056	0.0263t + 11.416	2.7496	A
Aksu	11.163	0.608	−0.086	0.0409t + 10.323	5.0099	A
Kuerle	8.378	0.598	0.075	0.031t + 7.738	3.6817	A

precipitation or air temperature. In other words, during a wet, dry or normal year, the change of air temperature and precipitation in the same year is similar.

Table 9 shows that there is a significant level of annual runoff of the Aksu and Kaidu rivers and that there is a relationship between the discharge of these two rivers and changes in temperature and precipitation. However, the change in the three variables for the Hetain and Yarkant rivers are not consistent and the assumption of H_0 is disproved (Table 9). These results reveal that the hydrological process in the Tarim River watershed is very complex. They also reveal that the reasons for changes in water resource are varied. In future research, a watershed should therefore be regarded as an independent research unit in arid areas.

Table 6 | Temperature correlation matrix (significance level $a < 0.05^{*}$; $a < 0.001^{**}$)

	Aksu	Kashi	Hetan	Tashkergan	Tuergate	Aheqi	Bayinbulker
Kuerle	0.914**	0.345*	0.800**	0.329*	0.617**	0.714**	0.562**
Aksu		0.442**	0.773**	0.325*	0.684**	0.733**	0.398**
Kashi			0.309*	0.007	0.255	0.392*	−0.013
Hetan				0.544**	0.810**	0.885**	0.468**
Tashkergan					0.647**	0.481**	0.255
Tuergate						0.810**	0.322*
Aheqi							0.474**

Table 7 | Precipitation correlation matrix (significance level $a < 0.05^{*}$; $a < 0.001^{**}$)

	Aksu	Kashi	Hetan	Tashkergan	Tuergate	Aheqi	Bayinbulker
Kuerle	0.425**	0.422**	0.343*	0.068	0.282	0.202	−0.047
Aksu		0.496**	0.284	0.050	0.022	0.246	0.027
Kashi			0.631**	0.069	0.351*	0.660**	0.053
Hetan				0.117	0.255	0.627**	−0.069
Tashkergan					0.243	−0.048	−0.186
Tuergate						0.516**	0.109
Aheqi							0.158

Table 8 | Wilcoxon's two-viable correlation test between temperature, precipitation and annual runoff

River	Item	z_w	*a* (Asymp. Sig. 2-tailed)	Significant level	Judgement
Hetain River	Precipitation	−0.643	0.521	Not significant	Accepted H_0
	Temperature	−0.854	0.393	Not significant	Accepted H_0
Aksu River	Precipitation	−0.554	0.580	Not significant	Accepted H_0
	Temperature	−1.237	0.216	Not significant	Accepted H_0
Yarkant River	Precipitation	−0.688	0.491	Not significant	Accepted H_0
	Temperature	−0.892	0.372	Not significant	Accepted H_0
Conclusion	The assumption that there is a correlation between the annual runoff volume and the precipitation or temperature is accepted (significance level a >0.05 means not significant).				

Table 9 | Kendall's *W* test to reveal the similarity between annual runoff and temperature and precipitation

Item	Hetain River	Yarkant River	Aksu River	Kaidu River
Chi-Square	3.048	4.333	46.333	19.419
Kendall's *W*	0.036	0.052	0.552	0.313
Concomitant probability	0.218	0.115	0.000	0.000
Significant level	Not significant	Not significant	Extremely significant	Extremely significant
Judgement	Accepted H_0	Accepted H_0	Refused H_0	Refused H_0
Conclusions	A	A.	B	B

Table 10 | Effect of precipitation and temperature on annual runoff

River	Item	R^2	F	T	Durbin-Watson	Significant level
Hetain River	Precipitation	0.031	1.263	−1.124	2.099	0.268
	Temperature	0.035	1.445	1.202	1.947	0.236
Aksu River	Precipitation	0.049	2.077	1.441	1.170	0.157
	Temperature	0.238	12.493	3.535	1.442	0.001
Yarkant River	Precipitation	0.080	3.491	−1.868	2.431	0.069
	Temperature	0.090	3.949	1.987	2.491	0.054

The increasing precipitation represents the increase of the total amount of water resources, but in this paper, the increase in runoff is affected mainly by glacier melt and the total amount of water resources is not increased. Increased glacier melt due to an increased temperature would initially increase the runoff, which would subsequently decrease since the glacier is finite in volume, and renewable water supplies are likely to decline. Changes in headstream annual runoff of the Tarim River are caused by changes in temperature and precipitation, but the effect of glacier meltwater will be limited in the future.

We use the non-parametric statistical and parametric test results to conduct the preliminary research (Table 10). Viewing the results of Wilcoxon's two-variable correlation tests in Table 8, the Z_w values and the concomitant probabilities indicate a correlation between annual streamflow of the three rivers and temperature. For example, all the Z_w values of temperature are lower than that of precipitation, and the significance values of the concomitant probabilities is also similar. This reveals that the correlation between annual runoff and temperature is more significant. The statistical results of the parameters in Table 10 reveal the influence of temperature and precipitation change on annual runoff, using the variables R^2, F, T and Durbin-Watson. The correlation between annual runoff and temperature is more significant than the correlation between annual runoff and precipitation in the Hetian, Aksu and Yarkant rivers.

Annual runoff will be increased by 5% if the average temperature in the Tarim River Watershed increases by 0.5°C, according to a regression model (Wu *et al.* 2003). Our research showed that the average temperature of the Yarkant and Hetain rivers increased by 0.5°C during the 10-year period of 1994–2003, and the 10-year average annual runoff increased by 5.6%. We therefore consider that the increase in annual runoff of headstreams of the Tarim River is mainly caused by increasing temperature. Renewable water supplies are eventually likely to decline under global warming (Abu-Taleb 2000) however, if the glacier shrinkage during the last 30 years corresponds to rising temperatures in the high mountain region of Xinjiang (Liu & Wang 1999). Glacier meltwater, the main source of the Tarim River, should therefore be considered as a depleting resource.

CONCLUSIONS

We have presented a study of annual runoff, precipitation and temperature in the headstream areas of the Tarim River. The following conclusions can be drawn.

1. The analyzed results of the long-term change trends of annual runoff, temperature and precipitation in the headstream of the Tarim River Watershed over the last 50 years show that the runoff, temperature and precipitation have all increased. The amount of change in annual runoff varies between different rivers, but it has significantly increased since 1994 in all cases.
2. There is a correlation between annual runoff, temperature and precipitation. The change in annual runoff of the Aksu and Kaidu rivers is consistent with the change in temperature and precipitation. However, the changes of the three variables for the Hetain and Yarkant rivers are not consistent. The annual runoff of these rivers is increasing mainly because of increasing temperature. The precipitation in the study area is not uniformly distributed over time and space. The correlations between temperature and

precipitation are not uniformly distributed across areas of mountains and plains.

The relationship between the changes in annual runoff and climate change in the Tarim River watershed needs to be verified by further studies; we suggest intensifying studies on alpine glaciers in the headstream areas of the Tarim River watershed in the future. In addition, further work on the relationship between climate change and water resources should consider the separate watersheds. Global warming can accelerate the hydrological cycle and renewable water supplies are likely to decline. Glacier shrinkage will bring problems for water resource management in the future.

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