Available online at www.sciencedirect.com
ScienceDirect
Journal of Environmental Sciences 19(2007) 488–493
JOURNAL OF ENVIRONMENTAL SCIENCES
ISSN 1001-0742
CN 11-2629/X
www.jesc.ac.cn

Effects of climate change on water resources in Tarim River Basin, Northwest China

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Revised 20 August 2006; accepted 24 November 2006

Abstract

Based on hydrology, temperature, and precipitation data from the past 50 years, the effects of climate change on water resources in Tarim River Basin in Northwest China were investigated. The long-term trends of the hydrological time series were detected using both parametric and nonparametric techniques. The results showed that the increasing tendency of the temperature has a 5% level of significance, and the temperature increased by nearly 1°C over the past 50 years. The precipitation showed a significant increase in the 1980s and 1990s, and the average annual precipitation exhibited an increasing trend with a magnitude of 6.8 mm per decade. A step change occurred in both the temperature and precipitation time series around 1986. The streamflow from the headwater of the Tarim River exhibited a significant increase during the last 20 years. The increase in temperature, precipitation, and streamflow may be attributed to global climate change.

Key words: climate change; temperature; precipitation; streamflow; Tarim River

Introduction

Water is the foundation of the composition, development, and stability of oasis ecosystems in arid areas. It determines the evolution of the ecological environment, including the two contrary processes of oasis formation and development and of desertification, and it is the key ecological factor in arid areas. It is widely recognized that human activities will affect water resources and hydrological processes. The most obvious effect is climate change, which has resulted in the increase of global temperature and modified precipitation patterns. One of the most significant consequences of climate change may be the alternation of the regional hydrological cycles and subsequent changes in water resources and streamflow regimes. The effects of changes in temperature and precipitation on hydrology have been investigated by many hydrologists. Salinger *et al*. (1995, 1996) concluded that air temperatures in Australia have risen by 0.5–0.9°C since the beginning of the century. Muttiah and Wurbs (2002) found that both the average temperature and precipitation of the United States increased during the 20th century, mostly due to the increases in intense rainstorms. The variability of runoff and water resources is particularly higher for drier climates, e.g., a higher percentage change in runoff resulting from a small change in precipitation and temperature in arid or semi-arid regions (Gan, 2000). It is very important for water resource managers to know and prepare to deal with the effects of climate change on hydrological cycles and streamflow regimes.

Located in the arid area of north-western China, Tarim River, about 1321 km long, is the longest continental river in the world. It is mainly fed by glacial/snow melt water, which accounts for 48.2% of the total water volume in the basin. The ecological environment in the Tarim River Basin is extremely vulnerable. The contradiction between ecological protection and economic development is increasingly extrusive in the exploitation and utilization of water resources, and the sustainable development of the regional society and economy is seriously restricted. Significant improvements have been made in regulating the streamflow of the Tarim River for flood control and water supply mainly for agricultural purposes during the past several decades. These improvements have made a great contribution to the development of the economy in Tarim River Basin. However, its negative influences such as deforestation, desertification, and increased soil salinity have also been considerable. In particular, the downstream water curtailment brought about great negative effects for the ecosystem in the Tarim River Basin. The stream flow of a 321-km section of the river downstream was completely cut off in 1970, and the lakes at the tail of Tarim River, Lop Nor and Lake Taitema, were dried up in 1970 and 1972, respectively. The groundwater level in most regions downstream decreased to 8–10 m. Some eco-environmental problems occurred, including the serious degeneration of the natural vegetation that relies on groundwater for existence, the death of the herbs dominated by *Phragmites*

Project supported by the Pilot Project of Knowledge Innovation Program of Chinese Academy of Sciences (No. KZCX2-YW-127) and the National Natural Science Foundation of China (No. 90502004, 40671014).
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communis, *Apocynum venetum*, *Athagi pseudathagi*, etc., the degeneration of *Tamarix chinensis* shrubbery and the *Populus diversifolia* forests in large areas, serious wind erosion and land desertification, as well as the seriously damaged ecosystems. The area in the lower reaches of Tarim River has become one of the regions with the most serious problems of exploitation and utilization of water resources in western China. Both local and central governments have paid significant attention to the altered hydrological regime of Tarim River ecology. In an attempt to restore the ecological system, ecological water releases from Boston Lake through Daxihaizi Reservoir were carried out several times. It was realized that these water releases were beneficial to the potential restoration of the ecosystem (Chen *et al*., 2004).

Investigation of the relationship between climate change and the available water resources is beneficial for the efficient water resource management (Bordi and Sutera, 2001). To estimate the possible effects of climatic changes on the hydrological process and water availability is particularly important for any work aimed at supporting the sustainable management and long-term planning of water resources. It is especially important in Tarim River Basin where the supply of water resources is a major constraint for further social development and ecological protection. It is therefore important to investigate the hydrological process and water resource availability, understand the causes of water scarcity, and on the basis of this investigation to formulate a new vision for the future water resources in the Tarim River Basin. In this article, climate and hydrology data from the past 50 years were used, the plausible long-term trends of the temperature and precipitation time series were detected, and the sensitivity of runoff to climate change was investigated. The purpose of this study was to reveal the association between climate change and the variability of hydrological process response, elucidate the effects of climate change on hydrological processes and water resources, and offer decisional reference for the social and economic development of inland river basins in arid areas.

1 Study area and methods

1.1 Study area

The Tarim River Basin, with an area of 1.02×10^6 km^2, is the largest continental river basin in China. It is composed of 114 rivers of 9 water systems. The mean annual natural runoff of surface water is 3.98×10^{10} m^3, which is supplied by water converted from ice and snow and precipitation in the mountains. Hydrologically, Tarim River Basin represents a closed catchment, and it is a unique freshwater ecosystem located near Taklamakan Desert, the largest desert in China.

The mainstream catchment of the Tarim River is 1321 km in length. In its history, there have been nine water systems that have flowed into the mainstream of Tarim. Now only three water systems have a natural hydraulic relationship with the mainstream–Aksu River, Hotan River, and Yarkand River. Among these three headstream flows into Tarim River, Aksu River is the main source for supplying water to the mainstream of Tarim River, accounting for 73.2% of the total. The Hotan River and Yerkand River account for 23.2% and 3.6%, respectively (Chen *et al*., 2003). In the composition of the runoff, the glacial/snow melt water accounts for 48.2%. The interannual change of the annual runoff volume is small, the C_v values vary in a range of 0.15–0.25, and the maximum and minimum modular coefficients are 1.36 and 0.79, respectively. The seasonal runoff is quite badly distributed. The runoff volume in the flood season from June to August accounts for 60%–80% of the annual runoff volume; this indicates that the rivers are mainly fed by the mountainous glacial-snow melt water in the arid areas (Fig.1).

The Tarim River Basin has an extreme drought desert climate with an average annual temperature of 10.6–11.5°C. The monthly mean temperature ranges from 20 to 30°C in July and –10 to –20°C in January. The highest and lowest temperatures are 43.6°C and -27.5°C. The annual precipitation is 116.8 mm in the study area. It ranges from 200 to 500 mm in the mountainous area, 50 to 80 mm on the side of the basin, and only 17.4–25.0 mm in the central area of the basin. The temporal distribution of precipitation throughout the year is strongly heterogeneous. More than 80% of the total annual precipitation falls between May and September in the high flow season and less than 20% of the total falls from November to the following April.

1.2 Data collections

Because the Tarim River Basin covers more than two thirds of the area of Xinjiang and the impact of climate change usually involves a large area, both temperature and precipitation data from 77 meteorological stations from 1955–2000 and the precipitation from 61 rain gauges from 1956–2000 over all of Xinjiang were used in this study. Five time series of streamflow runoff during the past five decades from the Xehera, Sharikilank, Kaqung, Tongguzlok, and Uruwat hydrologic stations on the headstream of the three main tributaries, Hotan, Yarkand, and Aksu Rivers, were used.

1.3 Methods

As we know, both parametric and nonparametric tests may be employed for trend detection. However, in terms of the power of the test, i.e., the ability to distinguish between null hypothesis H_0 and alternative hypothesis H_1 (the

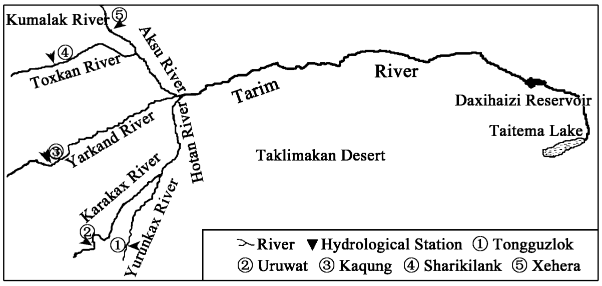

Fig. 1 Sketch map of the Tarim River Basin.

Mann-Kendall test for monotonic trends and the Mann-Whitney test for step changes) perform well in comparison to the parametric t-test (Belle and Hughes, 1984). In this study a nonparametric test was employed to detect possible trends in hydrological processes and climate change.

1.4 Mann-Kendall method

The test statistic is given as follows. In a Mann-Kendall test, the null hypothesis H_0 states that the data (X_1, X_2, ···, X_n) are a sample of n independent and identically distributed random variables. The alternative hypothesis H_1 of a two-sided test is that the distribution of X_k and X_j are not identical for all k and j. The Kendall's statistic S is:

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

Let time series x_i be ranked from i=1, 2, ···, n–1, and let x_k be ranked from k=i+1, ···, n. Each data point x_i is used as a reference point and is compared with all other data points x_j such that:

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

If the data set is identically and independently distributed, then the mean of S is zero and the variance of S is:

$$\operatorname{var}(S) = \left(n(n-1)(2n+5) - \sum_t t(t-1)(2t+5) \right) \Big/ 18 \tag{3}$$

where, n is the length of the data set, t is the extent of any given time, and $\sum$ denotes the summation over all times. Then the test statistic (Z_c)is given as:

$$Z_c = \begin{cases} \frac{S-1}{\sqrt{\operatorname{var}(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{S+1}{\sqrt{\operatorname{var}(S)}}, & S < 0 \end{cases} \tag{4}$$

The magnitude of the trend is given as:

$$\beta = \operatorname{Median}\left(\frac{x_i - x_j}{i - j}\right), \forall j < i \tag{5}$$

in which $1<j<i<n$. A positive value of β indicates an "upward trend", and a negative value of β indicates a "downward trend".

The Mann-Kendall test may then be stated simply as follows: null hypothesis H_0: β=0 (β is the slope of trend); significance level: p; test statistics: Z_c; rejected H_0: $|Z_c| > Z_{1-\alpha/2}$, in which $\pm Z_{1-\alpha/2}$ are the standard normal deviates, and α is the significance level for the test.

1.5 Mann-Whitney test for step trend

Given a data vector X=(x_1, x_2, ···, x_n), we partition X such that $Y=(x_1, x_2, \cdots, x_{n_1})$ and $Z=(x_{n_1+1}, x_{n_1+2}, \cdots, x_{n_1+n_2})$. The Mann-Whitney test statistic is given as:

$$Z_c = \frac{\sum_{t=1}^{n_1} r(x_t) - n_1(n_1 + n_2 + 1)/2}{(n_1 n_2 (n_1 + n_2 + 1)/12)^{1/2}} \tag{6}$$

in which $r(x_t)$ is the rank of the observations. The null hypothesis H_0 is accepted if $-Z_{1-\alpha/2} \leqslant Z_c \leqslant Z_{1-\alpha/2}$, where $\pm Z_{1-\alpha/2}$ are the $1-\alpha/2$ quantiles of the stand normal distribution corresponding to the given significance level α for the test.

2 Analyses

2.1 Trend of temperature and precipitation time series

There are two main ways that climate change affects water resources: natural transition and anthropogenic disturbance. The natural transition is a process in which climatic factors change the elements of the hydrological cycle and regional natural conditions, subsequently affecting the quality and temporal-spatial distribution of water resources. In an arid area, the long-term trend of a hydrological process certainly will be affected by climate change. The Tarim River Basin is an independent and closed hydrological system. The basic statistics for time series in the study area, including average, standard deviation, coefficient of variation, coefficient of skewness, minima, maxima, and range, are listed in Table 1.

Fig.2 exhibits the standardized average temperature and precipitation in the study area. It is obvious that both a monotonic trend and step changes occurred in both time series. The year 1986 was a cut-off point, when a significant step change appeared. Through the test of Mann-Whitney, the temperature and precipitation contradict the null hypothesis (Table 2). In other words, the two time series actually exhibit an obvious step change.

The long-term trend of annual temperatures and precipitation in the study area is determined using parametric and nonparametric techniques in this study. The result is given in Table 3. It is noted that the temperature of both the parametric t-test and the nonparametric Mann-Kendall test contradicted hypothesis H_0. The increasing trend of the temperature has a 5% level of significance. The precipitation test, on the other hand, supports the null hypothesis H_0, that is, the increasing trend of the precipitation does not have a 5% level of significance. It can be seen that the β and Mann-Kendall slope of both temperature and precipitation are greater than zero, meaning they increased monotonically. This indicates that the trend

Table 1 Statistics for the temperature and precipitation time series

Statistics	Mean	Standard deviation	Coefficient of variation	Coefficient of skewness	Maximum value	Minimum value	Range
Temperature (°C)	6.86	0.63	0.09	0.13	8.23	5.71	2.52
Precipitation (mm)	156.65	30.34	0.19	0.69	245.58	104.36	141.21

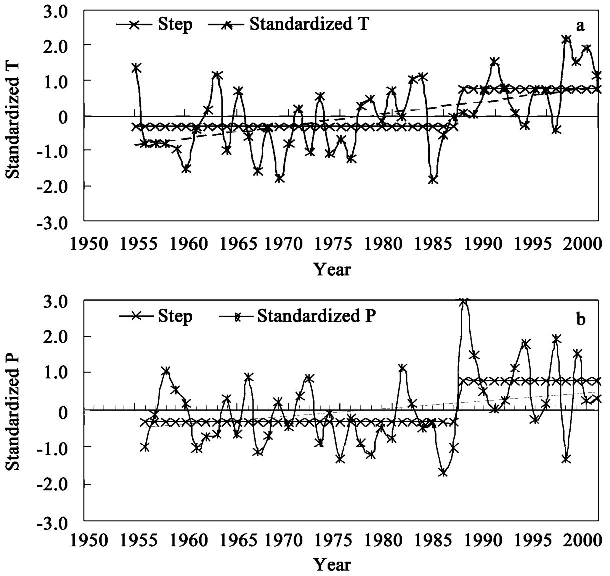

Fig. 2 Standardized average annual temperature (a) and precipitation (b) in the study area.

still existed, although the increasing trend of precipitation is not significant. Temperature and precipitation increased at the rates of 0.0252 and 0.6883, respectively. The mean temperature and precipitation before 1986 were 6.65 and 146.2, respectively, while those after 1986 were 7.34 and 179.7 (Table 4). Similar changes have been observed in Europe (Franks, 2002). During the past 50 years, the temperature increased by nearly 1°C, and the precipitation of the former and the latter step rose by 33.5 mm on average.

Since precipitation is a primary factor in the generation of river runoff, the precipitation in the study area and its pattern are thus further analyzed. The test result for the long-term trend of the precipitation is also shown in Table 2. The Mann-Kendall test supports H_0 at the 5% level of significance, but the t-test contradicts the hypothesis H_0. In other words, both the parametric and nonparametric tests show an increasing trend in precipitation, but they can not identify whether the trend is attributed to climate change or random fluctuation.

Table 2 Mann-Whitney test results of step trend for temperature and precipitation time series

Temperature				Precipitation			
Series		Test		Series		Test	
n_1	n_2	Z_c	H_0	n_1	n_2	Z_c	H_0
32	14	3.342	C	31	14	2.550	C

C: Contradicted.

In order to further investigate the spatial distribution of the precipitation in the study area, several distinct periods for the record from 1955 to 2000 were further examined: 1970s, 1980s, and 1990s. The spatial distribution of the precipitation changes over these three periods was analyzed. Fig.3 shows the ratio (%) of the difference between the average annual precipitation from 1950 to 2000 and the average annual precipitation over the distinct period (1970s, 1980s, or 1990s) to the average annual precipitation from 1955 to 2000 ($\Delta P/P$). The comparison shows that there is a significant decrease in the 1970s and a significant increase in the 1980s and 1990s. It dictated that the drying-up of the downstream mainstream of the Tarim River that occurred in the 1970s may be a result from not only anthropologic activities but also climate change. This result reflects that the study area has become warmer and wetter in the last two decades.

2.2 Trends detection of the runoff time series

Investigation of the relationship between climate change and the available water resources is beneficial for efficient water resource management (Bordi and Sutera, 2001). To analyze the long-term trend of the streamflow, three time series of streamflow runoff from the main tributaries, Hotan River, Yarkand River, and Aksu River, are used. The basic statistics for the time series, including average, standard deviation, coefficient of variation, coefficient of skewness, minima, maxima, and range, are listed in Table 5.

Statistics of the runoff shows that the total annual inflow volume of the three source tributaries varied in a range of 174×10^8–194×10^8 m^3 in average during the period from the 1950s–1990s. Moreover, in the 1990s the annual volumes of runoff from the headwaters of Aksu River and Yarkand River increased by 19×10^8 m^3 (for 10.9%), compared to the total in the 1950s. The results of both the t-test and the Mann-Kendall test show that the increase

Table 3 Monotonic trend test for temperature and precipitation time series

Item	t-Test				Mann-Kendall test		
	β_0	β_1	T_c	H_0	Z_0	β	H_0
Temperature	6.313	0.0233	15.38	C	3.428	0.0252	C
Precipitation	141.22	0.6706	23.61	C	1.702	0.6883	S

C: Contradicted; S: supported; significance level p=95%; T_c is statistics of t-test; Z_0 is statistics of Mann-Kendall test.

Table 4 Partitions of the temperature and precipitation time series

Item	No.	Time series	Length of record	Mean value	Standard deviation	Coefficient of variation
Temperature (°C)	1	1955–1986	32	6.65	0.56	0.08
	2	1987–2000	14	7.34	0.51	0.07
Precipitation (mm)	1	1956–1986	31	146.2	22.63	0.15
	2	1987–2000	14	179.7	33.20	0.18

Table 6 Monotonic shift test for three streamflow time series on tributaries

River	*t*-Test				Mann-Kendall test		
	β_0	β_1	T_c	H_0	Z_0	β	H_0
Aksu River	64.868	0.4344	14.049	C	3.327	0.3700	C
Yarkand River	71.072	0.0954	66.654	C	0.649	0.1113	S
Hotan River	46.238	-0.1230	37.840	C	-1.301	-0.1123	S

C: Contradicted; S: supported; significance level p=95%; T_c is statistics of *t*-test; Z_0 is statistics of Mann-Kendall test.

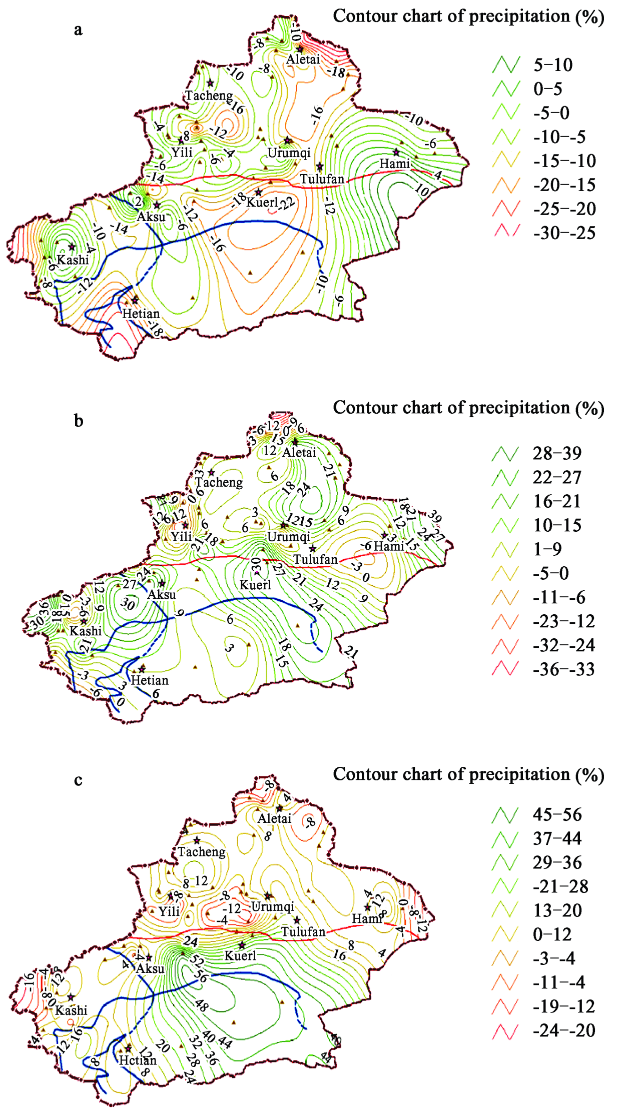

Fig. 3 Changes of average precipitation in 1970s (a), 1980s (b), and 1990s (c).

Table 5 Statistics for the inflow runoff time series from three tributaries (10^8 m^3)

Statistics	Aksu River	Yarkand River	Hotan River
Mean	74.21	73.17	43.59
Standard deviation	10.03	12.41	8.90
Coefficient of variation	0.14	0.17	0.20
Coefficient of skewness	1.09	0.33	0.60
Maximum value	101.54	105.14	68.92
Minimum value	58.21	50.53	24.49
Range	43.33	54.61	44.43

tendency on Aksu River has a 95% level of significance (Table 6). The streamflow on Yarkand River exhibits an obvious increasing trend with an increase coefficient of 0.41; the streamflow on Yarkant River exhibits a slight increasing trend with an increase coefficient of 0.13; and the streamflow on the Hotan River exhibits a slight decreasing trend with a decrease coefficient of 0.13. This indicates that actually there was an increasing trend in the total water volume in the headstream during the past 50 years. The effects of climate change on water resources in Tarim River Basin are obvious.

3 Conclusions

The following conclusions may be drawn from our study:

The study area seems to have become warmer in the last few decades. The results obtained by using both parametric and nonparametric techniques show that the increasing tendency of the temperature has a 5% level of significance, and the temperature increased by nearly 1°C over the past fifty years.

The test results for the long-term trend of the precipitation show that although the *t*-test contradicts the hypothesis H_0, the Mann-Kendall test supports the H_0 with a 5% level of confidence. Both parametric and nonparametric tests show an increasing trend in precipitation. The precipitation showed a significant decrease in the 1970s and a significant increase in the 1980s and 1990s, and the average annual precipitation exhibited an increasing trend with a magnitude of 6.8 mm per decade.

The research results through the Mann-Whitney test show that either the temperature or the precipitation contradicts the null hypothesis. A step change occurred in both temperature and precipitation time series around 1986. To find out whether this step change resulted from climate change, further studies with the combination of climatological analysis is required. The physical mechanism producing this kind of jump change needs further investigation.

The increasing trend of the Aksu River has a 95% level of significance; the streamflow of Yarkand River exhibits an increasing trend; and Hotan River shows a downward trend, but neither trend is distinct. This may be related to the geographic distribution of the headstreams.

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