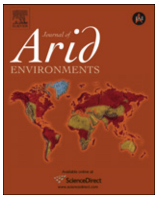
Journal of Arid Environments 74 (2010) 256–267

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv



Trends of major hydroclimatic variables in the Tarim River basin during the past 50 years

Zongxue Xu [a,c], Zhaofei Liu [a,b,*], Guobin Fu [b], Yaning Chen [c]

[a] Key Laboratory of Water and Sediment Sciences, Ministry of Education, College of Water Sciences, Beijing Normal University, Beijing 100875, China
[b] CSIRO Land and Water, Private Bag 5, Wembley, WA 6913, Australia
[c] Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China

ARTICLE INFO

Article history:
Received 14 May 2009
Received in revised form
21 August 2009
Accepted 25 August 2009
Available online 19 September 2009

Keywords:
Climate change
Mann–Kendall test
Trend
Water resources

ABSTRACT

The nonparametric Mann–Kendall test was used to detect the trends of major hydroclimatic variables in the Tarim River Basin, the largest inland river basin in China for the period of 1960–2007. Results showed that both mean annual air temperature and precipitation experienced an increasing trend, while annual streamflow demonstrated a mixed trend of decreasing and increasing: The mountainous region upstream showed an increasing trend and the region downstream exhibited a decreasing trend. Impacts of the increased air temperature on streamflow have shown different characteristics depending on location and seasons: it has positive effect on the runoff at mountainous region due to snowmelt and glacier-melt in spring, but negative effect on the runoff at plain area due to the increase of actual evaporation in summer. In addition, human activity contributed to the declining of streamflow in the arid plain oases at downstream of the Tarim River Basin. The results obtained in this paper can be used as a reference for the planning and management of water resources to maintain the health of the river system.

1. Introduction

The Tarim River Basin (TRB), the largest inland river basin in China, is located immediately north of the Qinghai-Tibetan Plateau whose orographic impacts together with the surrounding mountains including Tianshan Mountain, Kunlun Mountain and Altyn Ranges are a barrier to warm and moist air penetrating into the TRB (Zhang et al., 2003). Therefore, the study area has an extremely dry desert climate with limited precipitation and high potential evaporation. Although the annual precipitation in the mountainous headwater regions can reach about 250 mm, it is only 40–70 mm in the downstream regions of the TRB. In the Taklamakan Desert and the Lop Nur basin, the average annual precipitation is only about 12 mm. In contrast, the annual potential evaporation is about 1000–1600 mm, which makes the aridity index (ratio of annual potential evaporation to precipitation) one of the highest in the world.

The TRB is rich in natural resources, but the ecological environment in the basin is extremely vulnerable because of limited water resources (Chen et al., 2007). In the last several decades, both natural ecological processes and hydrological cycle in the study area have been deeply modified by human activity, which include, but are not limited to, expansion of irrigation land and rapid growth of population. For example, the population in the basin has increased by five times from 1950 to 1995, and the number of reservoirs has increased from two to eleven (Feng et al., 2001). Plants on both sides of the mainstream of TRB have gradually disappeared, soils have been salt-affected, desertification has become more frequent and some rivers have dried-up (i.e. zero-flow in the river channel).

Besides the impact of human activity, the hydrological regime in the TRB has also been affected by climate change. According to the Fourth Assessment Report (AR4) from the Intergovernmental Panel on Climate Change (IPCC), observational evidence for all continents and most of oceans showed that many natural systems are being affected by regional climate change, particularly by the increase of air temperature. Growing evidence indicates that there is high confidence that some effects on hydrological systems are occurring (Rosenzweig et al., 2007). The management and planning of water resources increasingly need to incorporate the effects of global climate change in order to accurately predict future supplies (Fu et al., 2007a), particularly in arid and semi-arid regions, where water availability is more sensitive to precipitation and air temperature (Chen et al., 2006). Much of the runoff in the

---

[*] Corresponding author. Tel.: +86 10 58803654; fax: +86 10 58801136.
E-mail address: zhfl@mail.bnu.edu.cn (Z. Liu).

0140-1963/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jaridenv.2009.08.014

TRB is generated in mountainous regions of the basin, which are covered by snow and glaciers. Increased air temperature in these regions could induce more runoff from the melting of snow and glaciers. However, more actual evaporation can be expected due to the increase of air temperature. This conclusion can be obtained on the basis of the general relationship between streamflow-precipitation-temperature and climate elasticity of streamflow (Fu et al., 2007b).

Several studies have detected the trends of hydroclimatic variables including annual precipitation, air temperature and runoff time series in the TRB (Xu et al., 2004, 2006, 2008; Chen et al., 2006, 2007; Hao et al., 2008). For example, Xu et al. (2004) documented the impact of climate change on water resources in the TRB and concluded that precipitation and the streamflow from the headwater of the Tarim River exhibited significant increasing, but a decreasing trend has been detected in the streamflow of the mainstream of the river. Xu et al. (2006) found that an increasing trend in precipitation was the main reason for the increase of runoff in the headwater catchment of the TRB during the last several decades. They further concluded that the impact of precipitation on runoff generation was greater than that of air temperature, while the impact of precipitation on actual evaporation amount is less important than that of air temperature. Mao et al. (2006) found that streamflow in the headwater catchment showed an increasing trend in the past 40 years, and there was a more significant trend from 1994 to 2002.

Most of the previous studies in the literature were conducted on an annual basis. The problem is that the increase of runoff in early spring due to the increase of air temperature and snowmelt might be offset by the declination of streamflow in summer due to the increase of actual evaporation. It was reported that an earlier occurrence of peak river flow in spring and an increase of base flow in winter in basins with important seasonal snow cover in North America and northern Eurasia were in agreement with local and regional climate warming in those areas (IPCC, 2007). The primary objective of this study is then to detect the trends of major hydroclimatic variables with monthly data series during the past five decades, which could give more detailed information than that on annual data. The results of this study can be used to support future planning and management of water resources for the strategy to maintain the health of the river system, especially under future global climate change scenarios.

2. Methodology and data description

2.1. Study area description

The TRB (Fig. 1), mainly located in Northwest China between 73–97°E and 34–45°N, is the largest inland river basin in China. The eco-environment in the study area is very fragile and vulnerable. It covers 64% of the area in the Xinjiang Uygur Autonomous Region and consists of five autonomous states and 42 cities. The basin area within China is 996,000 km^2. The total area is 1,020,000 km^2. The Takelamagan Desert has an area of 337,600 km^2 and is located in the center of the basin.

The TRB is typically a closed, independent and self-balanced hydrological system (Jiang et al., 2005). The downstream reach of the Tarim River is a purely dissipative inland river without generation of runoff, while streamflow is generally produced in its headstreams and tributaries (Mao et al., 2006). Historically there are nine river systems and 144 tributaries with hydraulic linkages with the mainstream of the TRB. However, most of these river systems were gradually changed or dried up, losing their relationship with the mainstream of the Tarim River. Currently only three headstreams, Hotan River, Yarkant River and Aksu River, have a natural hydraulic linkage with the mainstream. These three headstreams are usually referred as the head catchment of the TRB in the literature. In addition, the Kaidu-Konqi River delivers water

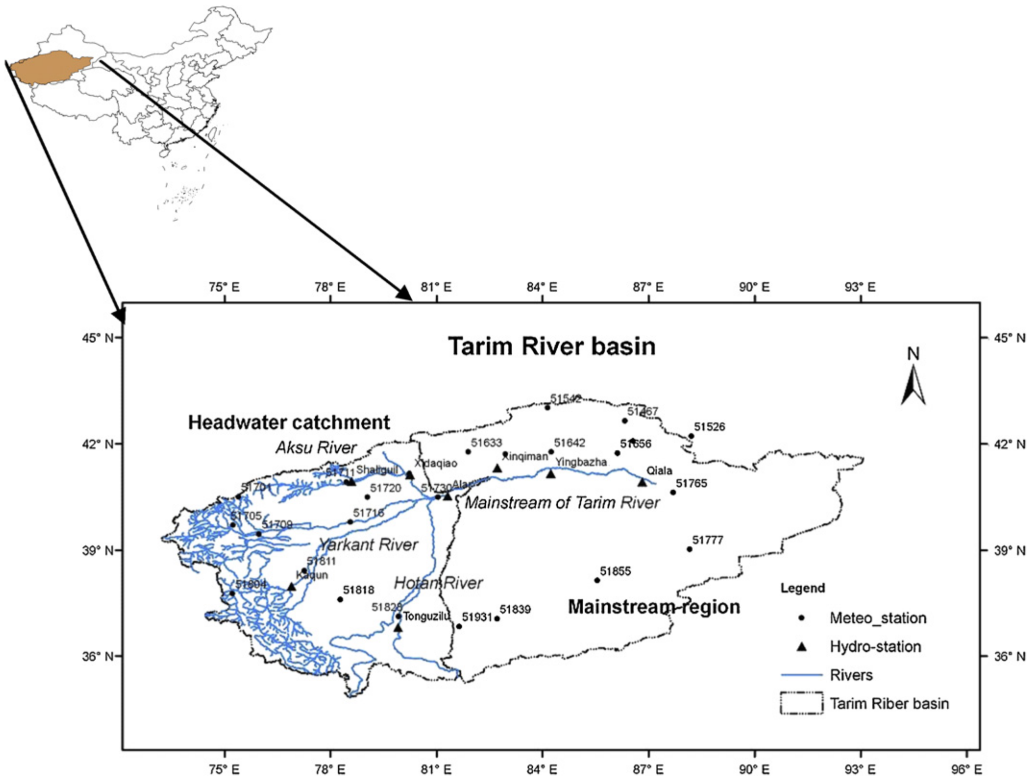


Fig. 1. Location of the Tarim River basin and the hydrometeorological stations used in this study.

to the lower reaches of the mainstream through the Kuta Main Canal (Song et al., 2000). The Kaidu-Konqi River has a hydraulic linkage with the downstream of the Tarim River, while other three rivers are associated with the upstream of the TRB.

Streamflow of the TRB is mainly generated from precipitation, glacial and snowmelt water in the head catchment, in which glacial and snowmelt water accounts for about 40% of the total runoff. Glacial and snowmelt water in spring season is vital for local agricultural development (Chen et al., 2007; Xu et al., 2008). Sources of streamflow in the headstreams are alpine glaciers and snowpack found at elevations of 2800–3500 m (Feng et al., 2001). After the runoff flows out of the mountainous regions, the surface water and groundwater exchange continually and nourish the plain oasis, a runoff-consumption area. Then the river reaches the desert areas, where the runoff eventually evaporates or flows into the lakes. The whole basin can be roughly divided into the headwater catchment and the mainstream region, for generation and consumption of streamflow, respectively (Fig. 1).

The mainstream region of the Tarim River has an extremely continental arid climate, with annual precipitation usually below 70 mm and the annual potential evaporation more than 1000 mm. Given the low rainfall of the mainstream region, runoff from the head catchment is the principal water resources, for driving regional economic development and maintaining the environmental balance. This area has become one of the regions with the most serious problems of over-exploitation and utilization of water resources in western China (Chen et al., 2007). Since the latter part of the twentieth century, ecosystems in this area have been substantially altered by human intervention. For example, a large reclamation area in the downstream region has turned to desert since the 1980s (Feng et al., 2001).

2.2. Data description

Observed monthly, seasonal and annual time series of precipitation, mean air temperature and streamflow in the TRB were used to estimate monotonic trends of these variables. There are 28 National Meteorological Observatory stations in or around the TRB, while 25 stations with continuous data series from 1960 to 2007 were selected in this study. The locations of the selected stations in the basin are shown in Fig. 1, and their altitudes and longitudes are listed in Table 1. Eight hydrological stations (Fig. 1), four in the head catchment and other four around the mainstream, were used in this study. In the head water catchment region, both Shaliguilanke and Xidaqiao stations provide measurement for the streamflow in the Aksu River, while Tonguziluoke and Kaqun stations control the streamflow from the Hotan River and Yarkant River, respectively. The sum of streamflow from these four stations is processed, approximately, as runoff generated in the head water catchment region in this study, although one tributary is not gauged. Alar station, the first gauge in the mainstream region, integrates all streamflow generated from the mountainous regions, after removal of water uses for irrigation, industry, and domestic purposes. The runoff at this point usually reaches its maximum value because downstream is generally only a runoff-consumption region. The difference of streamflow between this station and further downstream stations is resulted mainly from human activities (Hao et al., 2008). The period of study on streamflow time series is limited to 1960–2005, since streamflow data after 2006 have not been released by related water authorities.

2.3. Methodology description

The rank-based nonparametric Mann–Kendall test has been commonly used to assess the significance of monotonic trends in hydrometeorological time series, such as water quality, streamflow, air temperature and precipitation, in different regions across the world (e.g. Hirsch et al., 1982; Belle and Hughes, 1984; Chiew and McMahon, 1993; Burn, 1994; Lettenmaier et al., 1994; Gan, 1998; Lins and Slack, 1999; Douglas et al., 2000; Pilon and Yue, 2002; Yue et al., 2003; Fu et al., 2004; Xu et al., 2004, 2007; Hamed, 2008; Fu et al., 2009a, and others). The advantages of this method include that (1) it can handle non-normality, censoring or data reported as values “less than”, missing values, or seasonally and (2) it has a high asymptotic efficiency (Gan, 1998; Fu et al., 2004, 2009a). Therefore, this method was used in this study to detect long-term trend of hydrometeorological variables (e.g. precipitation, air temperature and streamflow) in the TRB.

Table 1
Meteorological stations used in this study.

ID	Station	Longitude (E)	Latitude (N)	Elevation (m)	Period of series
51467	Baluntai	86.33	42.67	1739	1957–2007
51526	Kumishi	88.22	42.23	922	1958–2007
51542	Bayinbuluk	84.15	43.03	2458	1957–2007
51567	Yanqi	86.57	42.08	1055	1951–2007
51628	Akesu	80.23	41.17	1104	1953–2007
51633	Baicheng	81.90	41.78	1229	1958–2007
51642	Luntai	84.25	41.78	976	1958–2007
51644	Kuche	82.95	41.72	1082	1951–2007
51656	Kurle	86.13	41.75	932	1958–2007
51701	Turgut	75.40	40.52	3504	1958–2007
51705	Wuqia	75.25	39.72	2176	1955–2007
51709	Kashi	75.98	39.47	1289	1951–2007
51711	Aheqi	78.45	40.93	1985	1957–2007
51716	Bachu	78.57	39.80	1117	1953–2007
51720	Keping	79.05	40.50	1162	1959–2007
51730	Alar	81.05	40.50	1012	1958–2007
51765	Tieganlik	87.70	40.63	846	1957–2007
51777	Ruoqiang	88.17	39.03	888	1953–2007
51804	Tashikurgan	75.23	37.78	3090	1957–2007
51811	Shache	77.27	38.43	1231	1953–2007
51818	Pishan	78.28	37.62	1375	1959–2007
51828	Hotan	79.93	37.13	1375	1953–2007
51839	Minfeng	82.72	37.07	1410	1956–2007
51855	Qiemo	85.55	38.15	1247	1953–2007
51931	Yutian	81.65	36.85	1422	1955–2007

For the cases that $n > 10$, the standard normal statistic Z is estimated by the following formula as (Hirsch et al., 1982; Gan, 1998):

$$Z = \begin{cases} (S-1)/\sqrt{Var(S)} & if \quad S > 0 \\ 0 & if \quad S = 0 \\ (S+1)/\sqrt{Var(S)} & if \quad S < 0 \end{cases} \tag{1}$$

Where

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i) \tag{2}$$

$$\mathrm{sgn}(\theta) = \begin{cases} 1 & if \quad \theta > 0 \\ 0 & if \quad \theta = 0 \\ -1 & if \quad \theta < 0 \end{cases} \tag{3}$$

$$\mathrm{Var}(S) = \left[n(n-1)(2n+5) - \sum_t t(t-1)(2t+5) \right] \bigg/ 18 \tag{4}$$

in which t is the extent of any given tie, $\sum_t$ denotes the summation over all ties.

The null hypothesis, H_0, meaning that no significant warming/cooling or wetting/drying trend is present, is accepted if the test statistic Z is not statistically significant, i.e. $-Z_{\alpha/2} < Z < Z_{\alpha/2}$, where $Z_{\alpha/2}$ is the standard normal deviate. Correspondingly, the presence of a trend is accepted if Z is statistically significant if $Z < -Z_{\alpha/2}$ or $Z > Z_{\alpha/2}$ (Gan, 1998). As it is possible that some stations have a trend of warming, others cooling, or some months wetting, and others drying, the two-sided hypothesis was chosen (Fu et al., 2004; Xu et al., 2007; Fu et al., 2009a).

In addition to identifying whether a trend exists, the magnitude of a trend was also estimated by a slope estimator β, which was extended by Hirsch et al. (1982) from that proposed by Sen (1968), defined as

$$\beta = \text{Median}\left(\frac{x_j - x_i}{j - i}\right) \quad \text{where} \quad 1 < i < j < n \tag{5}$$

In other words, the slope estimator β is the median over all possible combinations of pairs for the whole data set (Hirsch et al., 1982). A positive value of β indicates an 'upward trend' (increasing values with time), while a negative value of β indicates a 'downward trend' (Xu et al., 2007).

To explore the spatial distribution of trends for hydrometeorological variables, the magnitude of these trends was interpolated using ArcGIS package based on each individual station β value. Impacts of climate change and human activity on runoff for the TRB were detected based on the comparative analysis of the long-term trends of precipitation, mean air temperature and streamflow.

3. Results analysis and discussion

3.1. Trend of air temperature

The results of Mann–Kendall's test showed that the climate of the TRB watershed is warming during the last five decades. Twenty out of 25 stations exhibited a statistically significant increasing trend at the level of $\alpha = 0.05$ for annual series of air temperature (Fig. 2), and only two stations exhibited a slight and insignificant decreasing trend in the entire basin. This conclusion is consistent with previous studies on annual scale (Xu et al., 2004, 2006, 2008; Chen et al., 2006, 2007; Liu and Xu, 2007; Hao et al., 2008). However, those studies did not provide trend and magnitude for seasonal or monthly air temperature, which is the main objective of this study.

The increasing trends in winter months (December through February the following year) seem more dominant than those in spring months (March to May). For example, all 25 stations show a statistically significant increasing trend for seasonal mean temperature for winter (Fig. 2) and none of them are statically significant for spring season (Fig. 2). Summer (June to August) is the only season during that there is one station showing a statistically decreasing trend (Fig. 2). The fact that a statistically significant decreasing trend of daily air temperature in the warm season may be due to the cooling effects of irrigation (Lobell et al., 2006; Bonfils et al., 2008; Fu et al., 2009a), which was widely practiced in the mainstream region of the TRB. This may partly explain the difference of air temperature trend in head water catchment and mainstream regions for July and August: catchment region shows larger Mann–Kendall Z statistics and trend magnitudes than mainstream area (Fig. 3). March is the only month showing a decreasing trend of air temperature for the TRB, which is consistent with the results of an early study for the Yellow River basin (Fu et al., 2004). This needs a further investigation and probably is related to snow and glacier-melt in the early spring season.

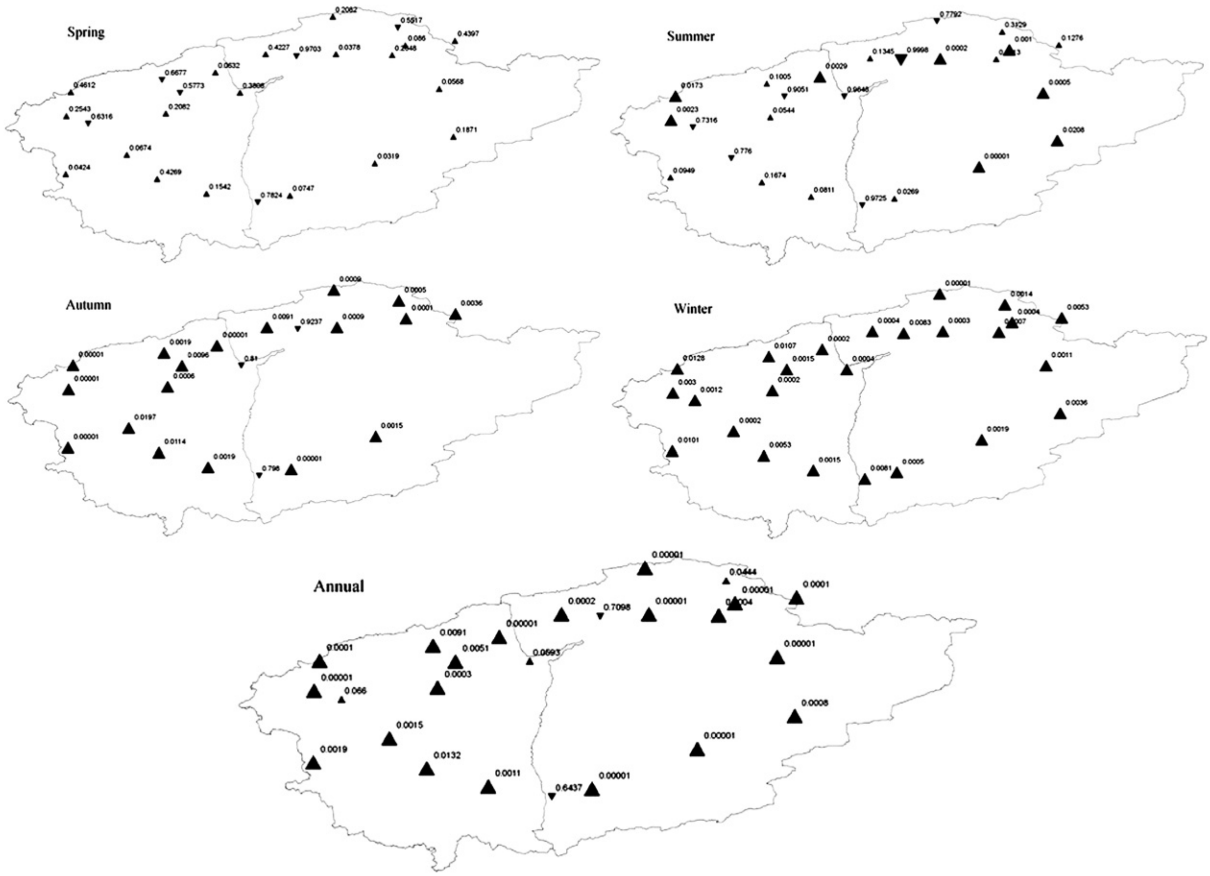


Fig. 2. Annual and seasonal trends of mean air temperatures at each station with its p-value in TRB (Black triangle: increase; upside-down black triangle: decrease. Large symbols indicate that they are statistically significant at $\alpha = 0.05$ levels).

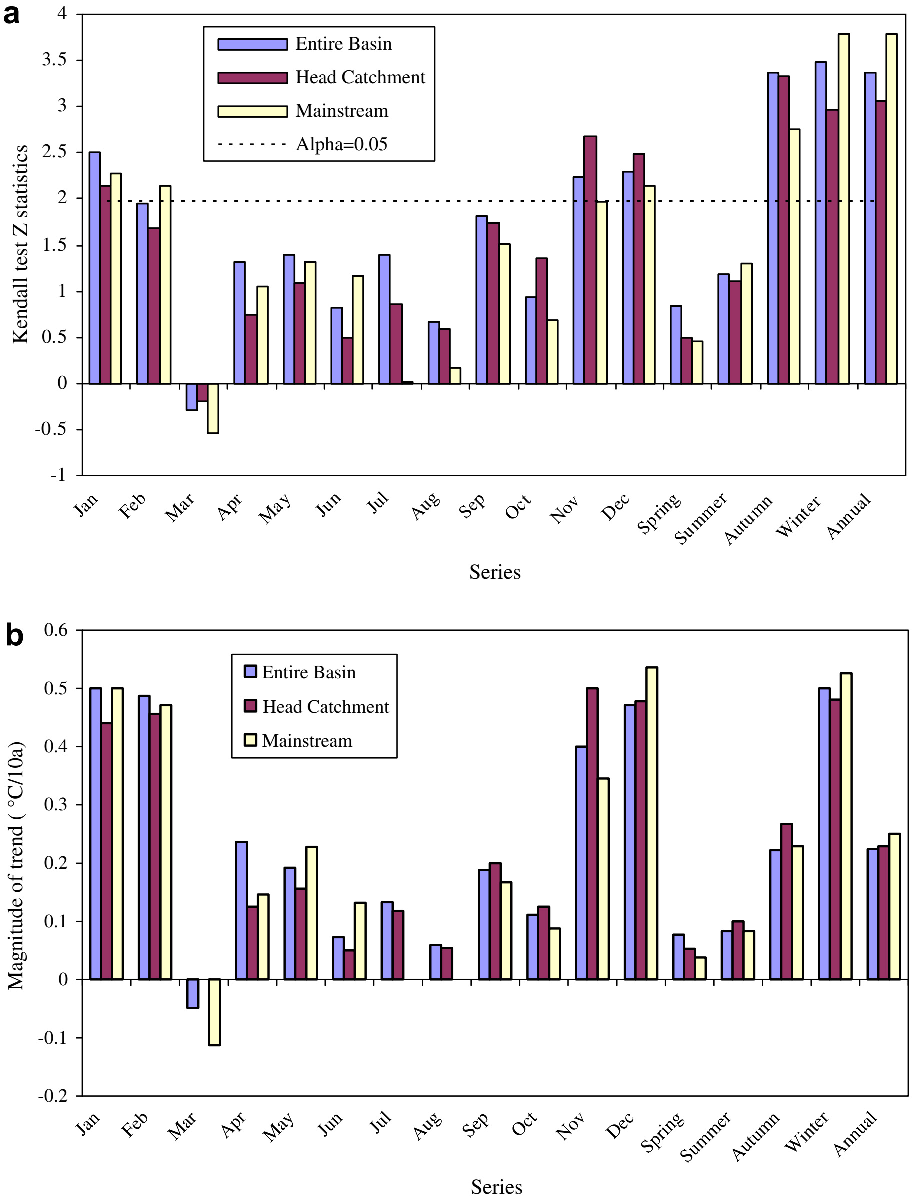


Fig. 3. Trends of monthly and annual air temperature a) Kendall test *Z* statistics and b) magnitudes of trend for the TRB.

Overall the annual means of daily mean air temperature have increased by 0.22 °C/10 yr, 0.23 °C/10 yr, and 0.25 °C/10 yr, for entire basin, head water catchment, and mainstream regions, respectively, during the last 50 years (Fig. 3). The magnitude of the increase in air temperature for the mainstream region is slightly greater than that for head water catchment and entire basin. It potentially implies that the natural consumption of water resources in the TRB has experienced an increasing trend due to more evaporation, resulting from higher air temperature. On a monthly scale, the greatest magnitude of the increase in air temperature occurred in January, February, November and December, during that the trends were about twice the magnitude of the annual increase (Fig. 3).

Spatial distributions of annual and seasonal magnitudes of increasing air temperature are shown in Fig. 4. Annual mean air temperature experienced the largest increasing trend in the upstream mountainous region of the Yarkant River catchment and the magnitude in the area could reach as high as 0.5 °C/decade, which is more than double of the basin average. The upstream mountainous regions are the main sources of runoff generation for the entire TRB and are covered with glaciers and snow. It implies that the streamflow of the TRB would be increased and resulted from the glacier and snow melt due to the increase of air temperature. In other words, water availability of the TRB would be sensitive to the changes of both precipitation and air temperature. The northern boundary area of the TRB also has a relatively great magnitude of increase for air temperature at 0.5–0.7 °C/decade. The majority of the catchment has a trend magnitude of air temperature at 0.1–0.3 °C/decade except that for the upstream region of the Hotan River, where a slightly decreased annual mean air temperature has been observed. All seasons have almost identical spatial distributions of magnitude for the increase of air temperature except that the magnitude in winter is much greater than other seasons and the annual value; while spring and autumn seasons have relatively smaller magnitudes of increase for air temperature (Fig. 4).

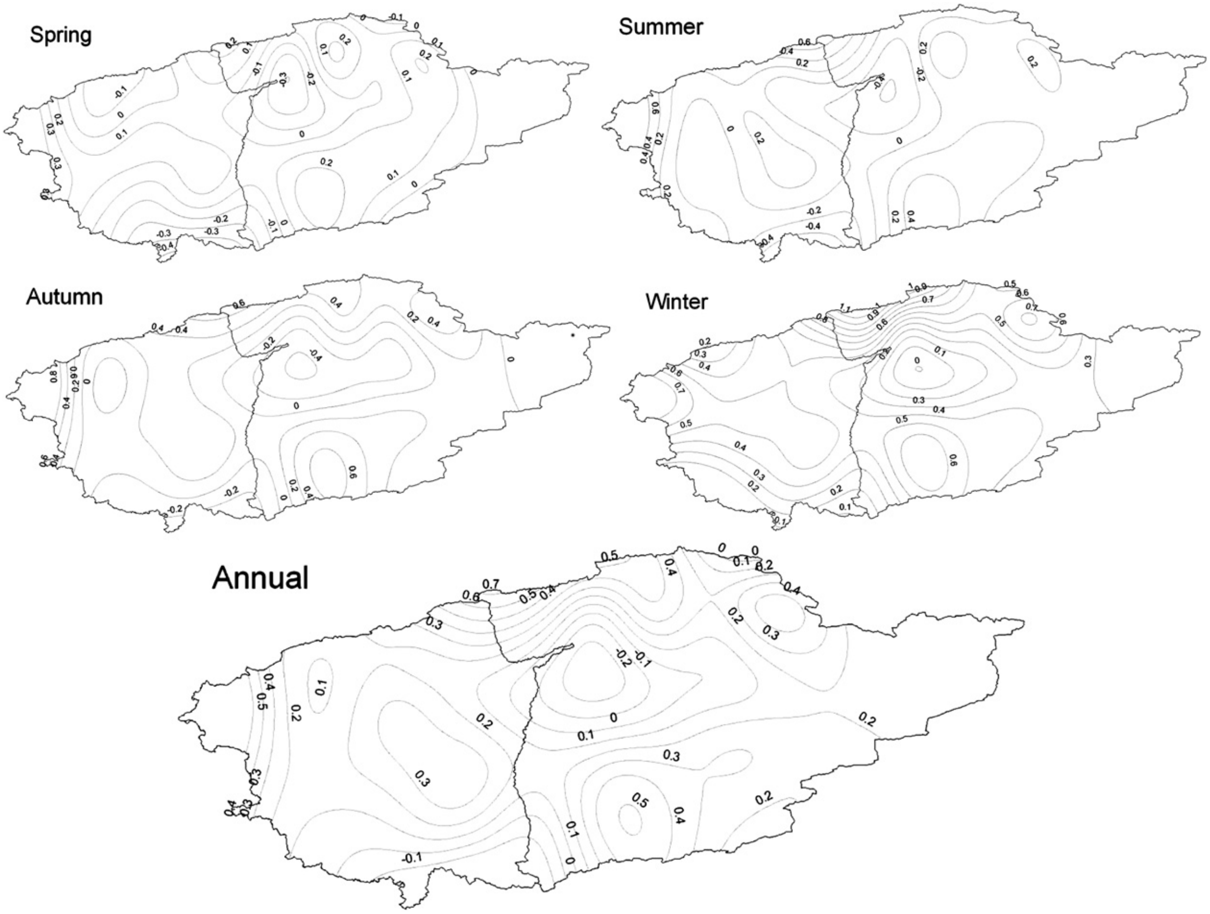


Fig. 4. Spatial distributions of trends for annual and seasonal air temperature in the TRB.

3.2. *Trends of precipitation*

Results of the Mann–Kendall test for monthly, seasonal and annual time series of precipitation indicate that the climate of the TRB has been getting wetter during the past five decades: 22 out of 25 stations exhibited an increasing annual precipitation trend and three of them are statistically significant at the level of $\alpha = 0.05$ (Fig. 5), and the annual precipitations for the entire basin and mainstream regions are also statistically significant at $\alpha = 0.05$ level (Fig. 6). This conclusion is consistent with results of previous studies (Xu et al., 2004, 2006, 2008; Chen et al., 2006, 2007; Liu and Xu, 2007; Hao et al., 2008).

Precipitation in most of months shows an increasing trend and the increasing trends in June are statistically significant at $\alpha = 0.05$ level for three regions and December precipitation is also statistically significant for the entire basin (Fig. 6). The number of stations with increasing trends and statistically significant stations in summer are larger than those of annual precipitation: 23 out of 25 stations exhibited an increasing summer precipitation trend and five of them are statistically significant at the level of $\alpha = 0.05$ (Fig. 5). May is the only month during which the monthly precipitation shows a slightly decreasing trend and its statistic Z value is very small. It is interesting to note that there are several months during that precipitation trends in the upstream and mainstream are of opposite sign to each other, such as January, February, September and November. It implies that the trends of precipitation are spatially heterogeneous among stations. The spatial distribution maps (Fig. 5) agree with this conclusion: all statistically significant increasing stations are located at mainstream region either for annual or seasonal precipitation. It is not difficult to understand this because the TRB is quite a large watershed that spans at different elevation zones.

The magnitude of the increasing trend shows that precipitation in the TRB had increased by 5.46–6.04 mm/decade in the past five decades with an upstream trend magnitude is slightly smaller than that in the mainstream region. The largest magnitudes of increase for monthly precipitation occurred in June, July and August, which made the magnitude of the trend in summer the largest for all seasons and contributed more than 50% of the annual magnitude. The magnitude of the trend in June is about four times that of annual precipitation.

Spatial distributions of trends for annual and seasonal precipitation time series are shown in Fig. 7. The magnitude of trend for annual precipitation varies from −3 mm/decade in the upstream region of the Yarkant River catchment and the midstream region of the Hotan River catchment to about 18 mm/decade in the northern part of the mainstream region. Both the magnitude and area of increased annual precipitation are larger than those of decreased annual precipitation. Seasonal trends of precipitation have similar spatial distribution as the trends of annual precipitation with two differences. Firstly, the magnitudes of trends in spring, autumn and winter seasons are much smaller than that in summer, especially in the mainstream region, where the magnitudes of trend for seasonal precipitation in spring, autumn and winter are close to zero. None of the stations has experienced a statistically significant increasing trend of seasonal precipitation for spring and autumn. Secondly,

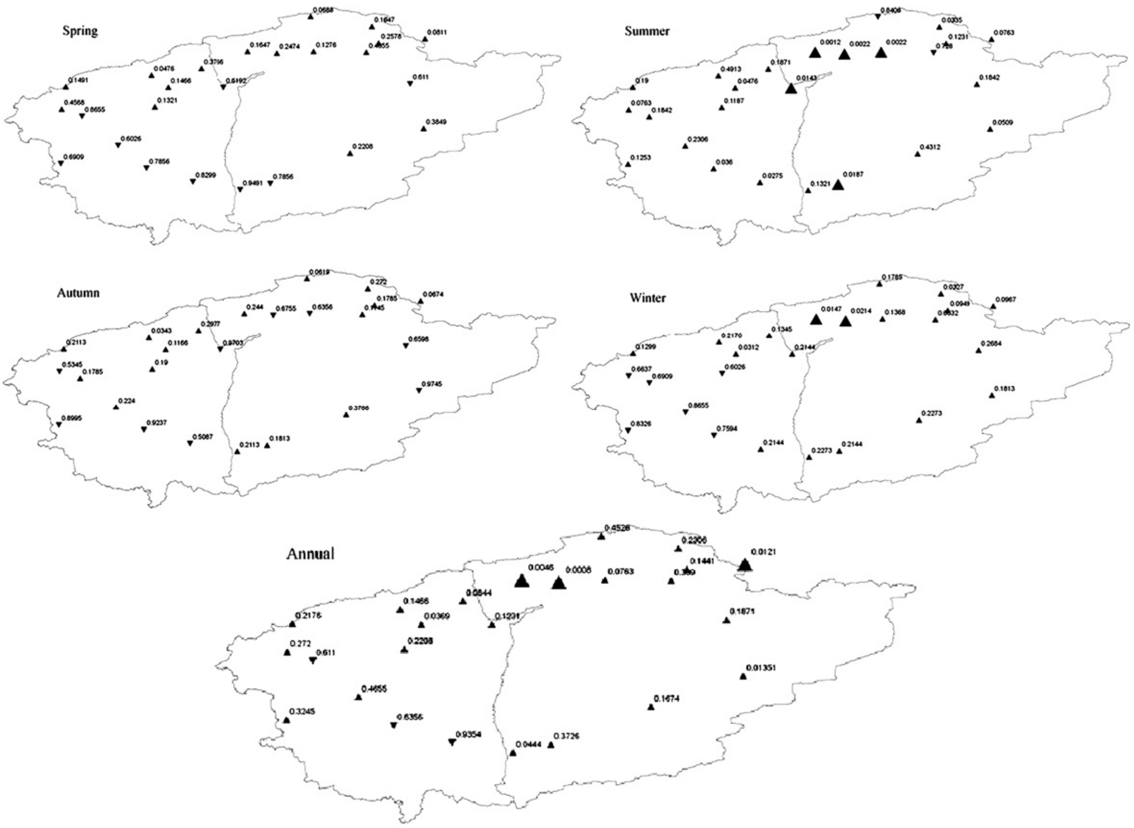


Fig. 5. Annual and seasonal mean trends of precipitation for each station with its p-value in TRB (Black triangle: increase; upside-down black triangle: decrease. Large symbols indicate that they are statistically significant at $\alpha = 0.05$ levels).

the relatively larger magnitudes of precipitation shifted from northern portion of mainstream to northern portion of upstream mountainous regions in spring, autumn and winter seasons.

3.3. Trend of streamflow

Annual streamflow in the headwater catchment exhibited an increasing trend, while that for the Alar station, the first hydrological gauging station in the mainstream, experienced a decreasing trend, although both of them are not statistically significant at $\alpha = 0.05$ of level (Fig. 8), which is consistent with previous results of Liu and Xu (2007). It indicates that the runoff in the mountainous regions in the headwater catchment had increased in the past five decades, while runoff flows into the mainstream region had decreased due to the consumption of water between two sections of the river.

On seasonal scale, streamflow in the headwater catchment showed an increasing trend for four seasons and two of them (spring and winter seasons) are statistically significant at $\alpha = 0.05$ of level, while streamflow at Alar station displayed an increasing trend for spring and an decreasing trend for summer, autumn, and winter, and both trends for spring and winter are statistically significant at $\alpha = 0.05$ of level (Fig. 8). It is interesting to note that statistically significant increasing trends of monthly streamflow have been detected for December, January, February, March and May in the headwater catchment, while none of these months have demonstrated a statistically significant increase of monthly precipitation, and both February and May even showed an insignificant decreasing monthly precipitation (Fig. 6). It implies that the contribution of glacier and snow melt due to higher air temperature to the streamflow played an important role. Chen et al. (2008) showed a declination of snow cover area for the TRB during last several decades. However, other studies, e.g. Xu et al. (2008) and Cui et al. (2005), showed a slow increasing trend for snow cover in the TRB. These contrary results for the trend of snow cover in the TRB might be resulted from different methods and data. It needs further investigations. However, empirical relationships between streamflow, precipitation, and air temperature indicate that streamflow is positively related to precipitation but negatively related to air temperature (Fu et al., 2007a,b). This implies that actual evaporation will increase under higher air temperature scenarios (Fu et al., 2009b). This may partly explain why monthly streamflow in November, December, January, and February at Alar station has experienced a statistically significant decreasing trend because those four months are only months showing a statistically significant trend of monthly air temperature (Fig. 3). Therefore, it can be concluded that the impacts of increase in air temperature on streamflow of the TRB have different effects depending on locations: it may result in the increase of runoff in upstream mountainous area due to snowmelt and glacier-melt, but may result in the decrease of runoff in plain area due to the increase of actual evaporation.

It should be pointed out that the hydrological regime of the mainstream is strongly affected by human activities, such as domestic water uses, irrigation, and water conservation projects. Streamflow is the only source for plain oases in the arid regions such as the TRB. The irrigated areas in the TRB has been expanded from about 3480 km^2 in the 1950s to 12,570 km^2 in the 2000s, and the consumption of water has increased from 5.0 billion m^3 to 15.5 billion m^3 accordingly in the same periods (Mao et al., 2006), while the numbers of artificial reservoirs increased from 2 to 11 and water storage capacity from 0.098 billion m^3 in 1950 to

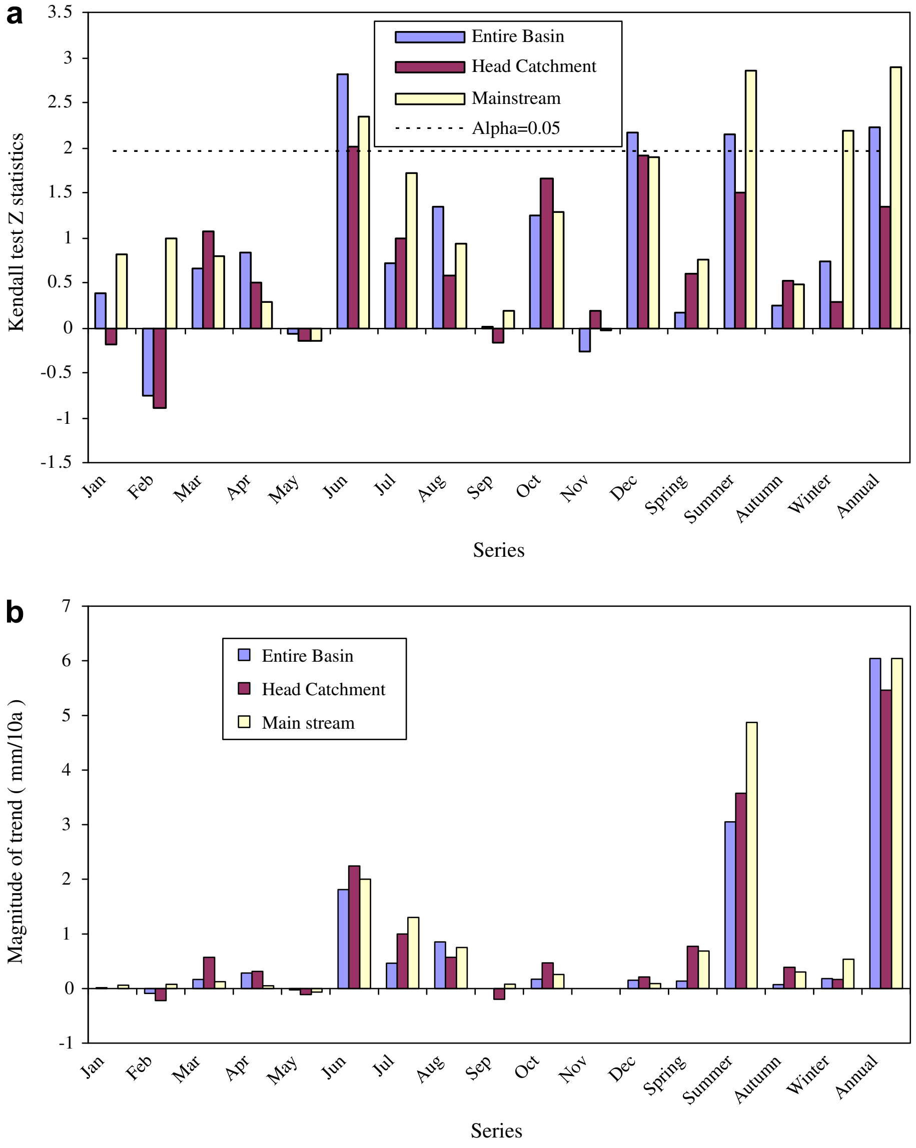


Fig. 6. Trends of monthly and annual precipitation a) Kendall test *Z* statistics and b) magnitudes of trend in the TRB.

1.07 billion m^3 in 1995 (Feng et al., 2001). The rapid changes in population also resulted in an increase of annual industrial and domestic water consumption of 0.01 billion m^3 (Feng et al., 2001). This is another primary reason why streamflow at headwater catchment and mainstream gauging stations showed different signs of trend during the past five decades. In fact, it is of no doubt that human activity is the predominant factor leading to the declination of streamflow in mainstream of the TRB during the past five decades. This conclusion is clearer if the trends of streamflow at four mainstream gauging stations: both the significance of decreasing in streamflow represented by Kendall statistic *Z* and the magnitude of trend are getting bigger from upstream to downstream stations except the magnitude of trend at Qialia gauging station, the last hydrological station in the main channel, which partly was due to inward water transfer after 2000 (Fig. 9).

The greatest magnitude of increasing in streamflow still occurred in summer, during which both precipitation and streamflow usually takes up more than 70% of the annual values, although the trend is not statistically significant. The increasing trend of summer precipitation is mainly responsible for this result, because the magnitude of increasing in summer precipitation is the greatest and the increasing trend of air temperature in summer is the second smallest one, comparing with other three seasons.

3.4. Attribution analysis

The trends of hydroclimatic variables detected in this study lead naturally to the question of attribution and dynamic mechanism. The trends of air temperature may result from global warming due to the greenhouse effect, "urban heat island", and long-term climate variability. Both significance and magnitude of increasing trend for air temperature in summer season is smaller than those in winter season, which leads to the decreasing range of intra-annual air temperature. Decreasing trends of diurnal daily air temperature range in Xinjiang were reported by Qian and Lin (2004). A statistically significant decreasing trend in the range of maximum and minimum daily air temperatures is to be expected as an indicator of a global warming signal (Karl et al., 1993). Therefore, there is reasonable evidence that some of the warming in the TRB is the result of global warming due to greenhouse emission.

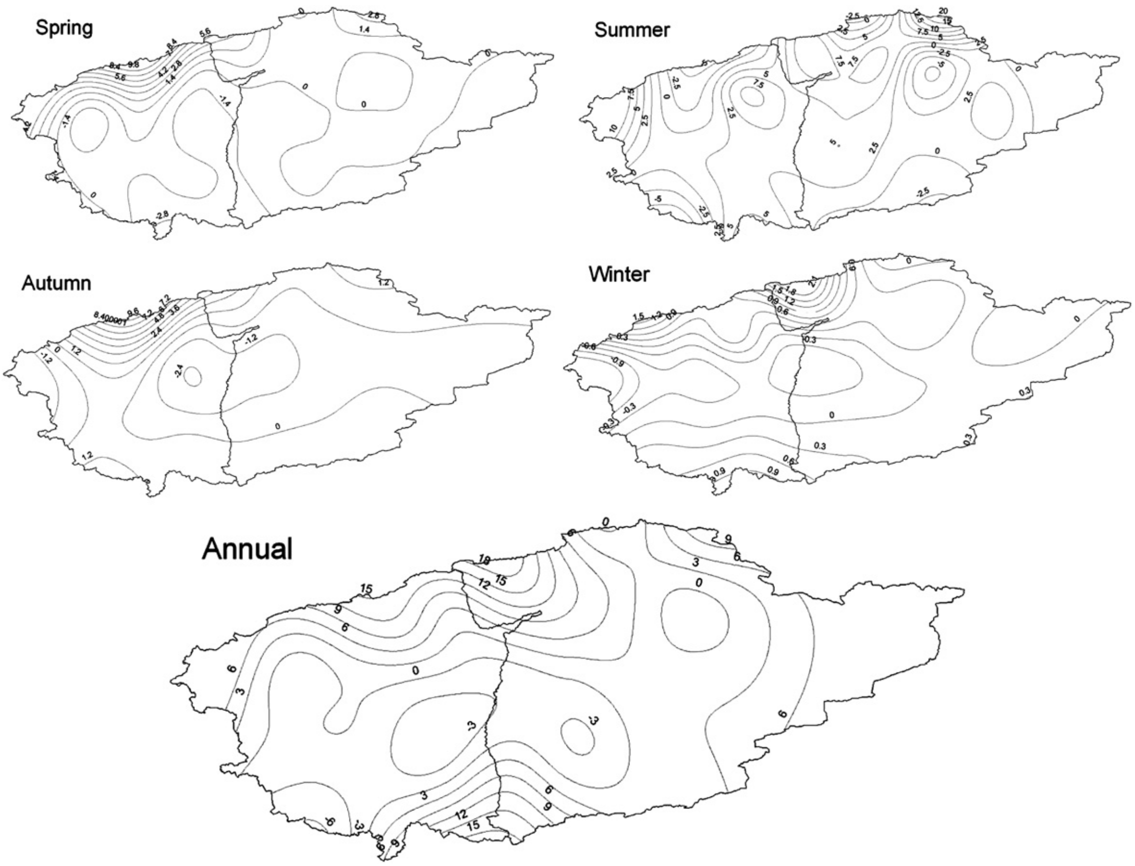


Fig. 7. Spatial distributions of annual and seasonal precipitation trend magnitudes for TRB.

The dynamic mechanism of increasing trend for precipitation is complicated and the possible attribution is a stronger westerly water vapor transport. Main water vapor sources of the TRB are in the west direction, including the Mediterranean Sea, Black Sea, Caspian Sea, the North Atlantic and the Arctic sea, of which the Mediterranean and Caspian Sea are sources for January and April, the Black Sea and Caspian Sea are for October, and the North Atlantic and Arctic sea are for July, respectively (Dai et al., 2007). The wetter tendency in these regions and the increase of westerly water vapor transport (Dai et al., 2007; Qian and Qin, 2008) might explain the increasing trend of precipitation in the TRB. The strengthening of the water vapor transport by the mid-high latitude westerly flows and the enhancement of the local hydrological cycle might have contributed to the increasing trend of precipitation in the TRB.

3.5. *Changes of eco-environmental system in the study area*

The changes of hydroclimate regimes could potentially result in many eco-environmental changes in the extremely arid environment such as the TRB. The actual effect is more serious than it appears today, and is usually irreversible. With the declination of streamflow in the mainstream of the TRB, the Lop Nur, the Taitemar Lake, and more than 320 km of the lower section at the lower reaches have dried up (Feng et al., 2005). Due to desiccation of the surface water courses, the groundwater level along the lower part of the downstream has dropped dramatically. For example, groundwater level along the lower part of the downstream has decreased by about 5 m from 1973 to 2000 (Hu et al., 2008). The average groundwater level in the downstream had declined to the lowest level required for the survival of most natural vegetation. Consequently, large areas of natural vegetation had degenerated in the downstream.

Water quality in the river has also changed in the basin. Before 1958, the Tarim River was a fresh water river with very clean water (Hu et al., 2008). The maximum salinity of surface water in the headwaters rose from 1.0 g/L in 1960 to 7.0 g/L in 2000, because of the expansion of upstream farmland and drainage water into the river system (Feng et al., 2005).

Since the 1950s, the condition and diversity of vegetation in the TRB have significantly declined. During the period of 1960–1990, forest biomass in the basin has decreased about 5-fold (Xun et al., 2001). With the increase in the intensity of development of water and land resources, natural *Populus euphratica* forest and shrubbery became seriously degraded. Concurrently, numbers of species also decreased rapidly. For example, herbaceous species decreased from 200 to 20 and wild animal species decreased from 26 to 5 (Zhou and Li, 1990).

Located between two deserts in the lower reaches, the "Green corridor" has an important strategic significance in preventing the merging of two deserts (Zu et al., 2003). Due to the desiccation of water courses, the "Green corridor" shrank continuously since the 1970s. National Highway 218, which runs through the "Green corridor", has been subjected to sand encroachment. Occurrences of disastrous floating dust and sand-dust storms increased substantially, and the living conditions have deteriorated. The large-scale natural vegetation has been destroyed.

Although annual precipitation exhibited an increasing trend for the past five decades, which in theory should result in more runoff, streamflow and water availability in mainstream region has

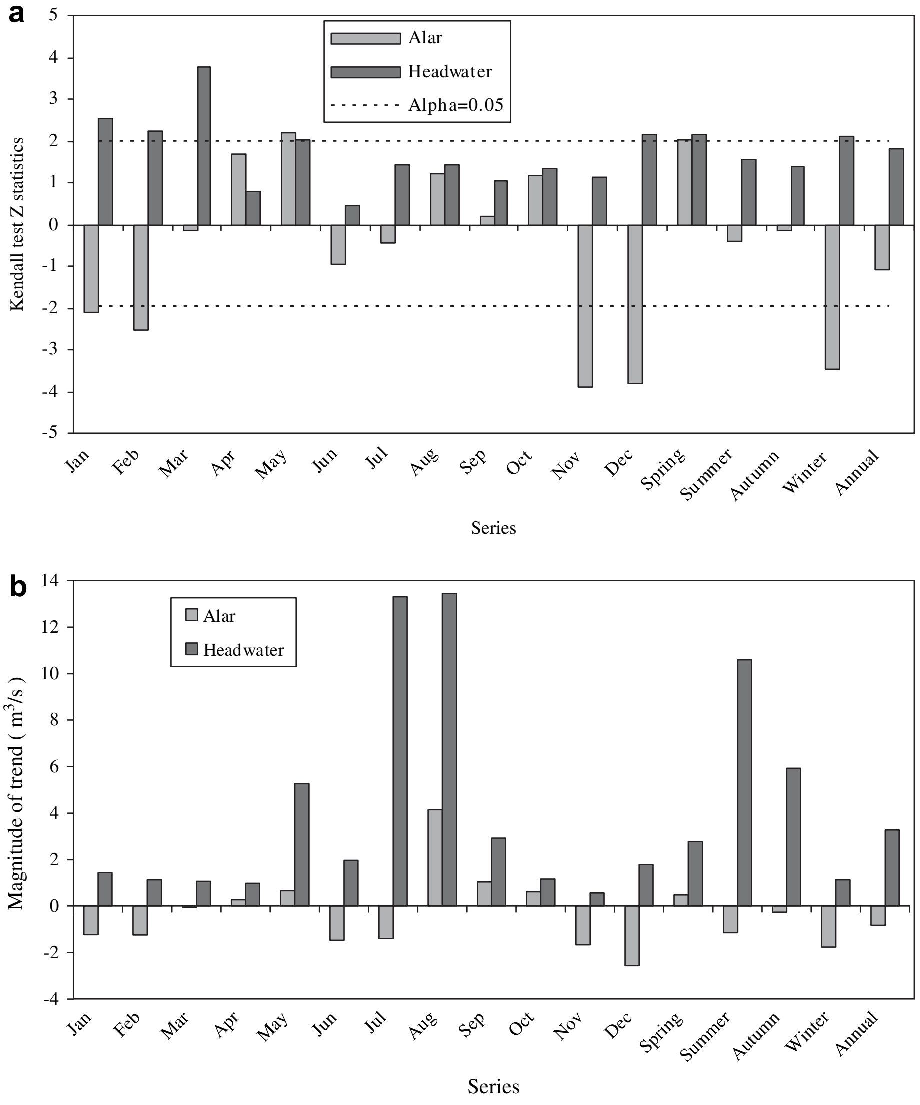


Fig. 8. Trends of monthly and annual streamflow a) Kendall test Z statistics and b) magnitudes of trend in the TRB (Notes: Streamflow for ‘Headwater’ is estimated by the sum of that from 4 stations in the headwater catchment).

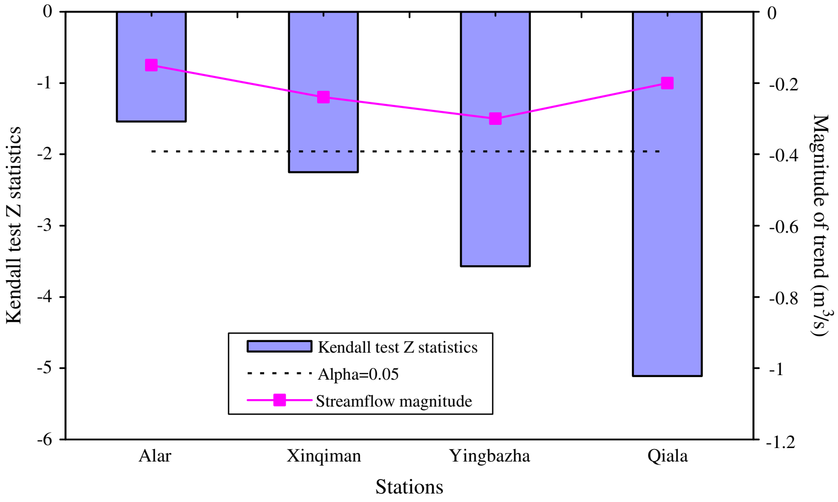


Fig. 9. Trend of annual streamflow for the mainstream region.

decreased and the environmental situation has been severely impaired because of limited water resources and dried-up of the mainstream. Therefore, it is clear that human activities, as well as the change and variability of climate all contributed to the trend of streamflow detected in this study.

4. Conclusion

Both mean annual air temperature and precipitation experienced an increasing trend for the TRB during the past five decades. Twenty out of 25 stations exhibited a statistically significant increasing trend at the level of $\alpha = 0.05$ for annual time series of mean air temperature. The increasing trends in winter months seem more significant than those in spring months and the absence of a statistically significant trend of daily air temperature in warm seasons may be due to the cooling effects of irrigation. The trend of increasing in precipitation is not as significant as that in air temperature. For example, 22 out of 25 stations exhibited an increasing trend of annual precipitation and only three of them are statistically significant at the level of $\alpha = 0.05$. The number of stations with increasing trend and statistically significant stations in summer are greater than those of annual precipitation.

The annual streamflow, however, demonstrated a mixture trend of decreasing and increasing: upstream mountainous region shows an increasing trend and downstream a decreasing trend, although both of them are not statistically significant at $\alpha = 0.05$ of level. A statistically significant trend of monthly streamflow has been detected for December, January, February, March and May for the headwater catchment, while none of these months have demonstrated a statistically significant increase of monthly precipitation, and both February and May even showed an insignificant decreasing trend of monthly precipitation. It implies that the contribution of glacier and snow melt, due to higher air temperature, is great to the streamflow. Therefore, the impacts of increase in air temperature on streamflow of the TRB have different effects depending on locations: it will result in the increase of runoff in upstream mountainous area due to snowmelt and glacier-melt, but will result in the decrease of runoff in plain area due to the increase of actual evaporation.

It should be pointed out that the hydrological regime of mainstream is strongly affected by human activities, such as domestic water uses, irrigation and water conservation projects. In fact, it is of no doubt that human activity is the predominate factor leading to the decline of streamflow in mainstream of the TRB during the past five decades.

The changes of hydroclimate regimes have resulted in many eco-environmental changes in the extremely arid environment of the TRB: shrinkage and disappearance of lakes, declination of groundwater level, deterioration of water quality, decrease of numbers for herbaceous and animal species, as well as the expansion of desert areas and increased frequency of floating dust and sand-dust storms.

The results of this study could be used as a reference for the planning and management of water resources to maintain the health of the river system, and for the protection of eco-environmental system of arid region in the TRB, especially for the cases under future global warming scenarios.

Acknowledgements

This study is jointly financed by the Knowledge Innovation Program (KZCX2-XB2-03) and Key Direction Project of Innovation Program (KZCX2-YW-127), Chinese Academe of Science. Assistance on data processing from Zhao F. F. and Mi Y. J. is greatly appreciated. Thanks also should be given to Dr Damian Andres Ravetta (Editor-in-Chief), Dr David Thomas (Associate Editor), Dr Nick Potter, Dr Stephen Charles and two anonymous reviewers for their invaluable comments and constructive suggestions to improve the quality of the manuscript and Sally Tetreault-Campbell for her assistance on the clarity of the manuscript.

References

Belle, V.G., Hughes, J.P., 1984. Nonparametric tests for trend in water quality. Water Resources Research 20 (1), 127–136.
Bonfils, D., Duffy, P.B., Santer, B.D., Wigley, T.M.L., Lobell, D.B., Phillips, T.J., Doutriaux, C., 2008. Identification of external influences on temperatures in California. Climatic Change 87, 43–55.
Burn, D.H., 1994. Hydrologic effects of climatic change in West Central Canada. Journal of Hydrology 160, 53–70.
Chen, Y.N., Li, W.H., Xu, C.C., Hao, X.M., 2007. Effects of climate change on water resources in Tarim river basin. Journal of Environmental Sciences 19, 488–493.
Chen, Y.N., Takeuchi, K., Xu, C.C., Chen, Y.P., Xu, Z.X., 2006. Regional climate change and its effects on river runoff in the Tarim Basin, China. Hydrological Processes 20, 2207–2216.
Chen, Y.N., Xu, C.C., Chen, Y.P., Li, Z.Q., Pang, Z.H., 2008. Response of snow cover to climate change in the periphery mountains of Tarim river basin, China, over the past four decades. Annals of Glaciology 49, 166–172.
Chiew, F.H.S., McMahon, T.A., 1993. Detection of trend or change in annual flow of Australian rivers. International Journal of Climatology 13, 643–653.
Cui, C.X., Wei, R., Li, Y., 2005. Long-term change of seasonal snow cover and its effects on runoff volume in the upper reaches of the Tarim river. Arid Land Geography 28 (5), 569–573 [in Chinese].
Dai, X.G., Li, W.H., Ma, Z.G., Wang, P., 2007. Water-vapor source shift of Xinjiang region during the recent twenty years. Progress in Natural Science 17 (5), 569–575.
Douglas, E.M., Vogel, R.M., Knoll, C.N., 2000. Trends in flood and low flows in the United States: impact of spatial correlation. Journal of Hydrology 240, 90–105.
Feng, Q., Endo, K.N., Cheng, G.D., 2001. Towards sustainable development of the environmentally degraded arid rivers of China: a case study from Tarim River. Environmental Geology 41, 229–238.
Feng, Q., Liu, W., Si, J.H., Su, Y.H., Zhang, Y.W., Cang, Z.Q., Xi, H.Y., 2005. Environmental effects of water resource development and use in the Tarim River basin of northwestern China. Environmental Geology 48, 202–210.
Fu, G.B., Chen, S.L., Liu, C.M., Shepard, D., 2004. Hydro-climatic trends of the Yellow River basin for the last several decades. Climatic Change 65, 149–178.
Fu, G.B., Barber, M.E., Chen, S.L., 2007a. The impacts of climate change on regional hydrological regimes in the Spokane River watershed. Journal of Hydrologic Engineering 12, 452–461.
Fu, G.B., Charles, S.P., Chiew, F.H.S., 2007b. A two-parameter climate elasticity of streamflow index to assess climate change effects on annual streamflow. Water Resources Research 43, W11419. doi:10.1029/2007WR005890.
Fu, G.B., Charles, S.P., Yu, J.J., Liu, C.M., 2009a. Decadal climatic variability, trends and future scenarios for the North China Plain. Journal of Climate 22, 2111–2123.
Fu, G.B, Charles, S.P., Yu, J.J., 2009b. A critical overview of pan evaporation trends over the last 50 years. Climatic Change 97, 193–214. doi:10.1007/s10584-009-9579-1.
Gan, T.Y., 1998. Hydroclimatic trends and possible climatic warming in the Canadian Prairies. Water Resources Research 34 (11), 3009–3015.
Hamed, K.H., 2008. Trend detection in hydrologic data: the Mann–Kendall trend test under the scaling hypothesis. Journal of Hydrology 349, 350–363.
Hao, X.M., Chen, Y.N., Xu, C.C., Li, W.H., 2008. Impacts of climate change and human activity on the surface runoff in the Tarim River basin over the last fifty years. Water Resources Management 22, 1159–1171.
Hirsch, R.M., Slack, J.R., Smith, R.A., 1982. Techniques of trend analysis for monthly water quality data. Water Resources Research 18 (1), 107–121.
Hu, H.L., Ye, M., Li, J.M., 2008. The water transfer effects on agricultural development in the lower Tarim River, Xinjiang of China. Agricultural Water Management 95, 59–68.
IPCC, 2007. Summary for policymakers. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., Van der Linden, P.J., Hanson, C.E. (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 7–22.
Jiang, L.W., Tong, Y.F., Zhao, Z.J., Li, T.H., Liao, J.H., 2005. Water resources, land exploration and population dynamics in arid areas: the case of the Tarim River Basin in Xinjiang of China. Population and Environment 26 (6), 471–503.
Karl, T.R., Jones, P.D., Knight, R.W., Kukla, G., Plummer, N., Razuvayev, V., Gallo, K.P., Lindseay, J., Charlson, R.J., Peterson, T.C., 1993. A new perspective on recent global warming: asymmetric trends of daily maximum and minimum temperature. Bulletin of the American Meteorological Society 74, 1007–1023.
Lettenmaier, D.P., Wood, E.F., Wallis, J.R., 1994. Hydro-climatological trends in the continental United States: 1948–88. Journal of Climate 7, 586–607.
Lins, H.F., Slack, J.R., 1999. Streamflow trends in the United States. Geophysical Research Letters 26 (2), 227–230.
Liu, Z.F., Xu, Z.X., 2007. Spatio-temporal distribution of hydrometeorological variables and their main impact factors in the Tarim river basin. Journal of China Hydrology 27 (5), 69–73 [in Chinese].

Lobell, D.B., Bala, G., Bonfils, C., Duffy, P.B., 2006. Potential bias of model projected greenhouse warming in irrigated regions. Geophysical Research Letters 33, L13709. doi:10.1029/2006GL026770.

Mao, Y.E., Xu, H.L., Song, Y.D., 2006. The utilization of water resources and its variation tendency in Tarim River Basin. Chinese Science Bulletin 51 (1), 16–24.

Pilon, P.J., Yue, S., 2002. Detecting climate-related trends in streamflow data. Water Science and Technology 45 (8), 89–104.

Qian, W.H., Qin, A., 2008. Precipitation division and climate shift in China from 1960 to 2000. Theoretical and Applied Climatology 93, 1–17.

Qian, W.H., Lin, X., 2004. Regional trends in recent temperature indices in China. Climate Research 27, 119–134.

Rosenzweig, C., Casassa, G., Karoly, D.J., Imeson, A., Liu, C., Menzel, A., Rawlins, S., Root, T.L., Seguin, B., Tryjanowski, P., 2007. Assessment of observed changes and responses in natural and managed systems. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., Van der Linden, P.J., Hanson, C.E. (Eds.), Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Climate Change 2007: Impacts, Adaptation and Vulnerability. Cambridge University Press, Cambridge, UK, pp. 79–131.

Sen, P.K., 1968. Estimates of the regression coefficient based on Kendall's tau. Journal of the American Statistical Association 63, 1379–1389.

Song, Y.D., Fan, Z.L., Lei, Z.D., Zhang, F.W., 2000. Research on Water Resources and Ecology of Tarim River, China. Xinjiang People's Publishing House, Urumqi, China.

Xu, C.C., Chen, Y.N., Li, W.H., Chen, Y.P., 2006. Climate change and response of hydrology for recent several decades in the Tarim River basin. Chinese Science Bulletin 51, 21–30.

Xu, C.C., Chen, Y.N., Li, W.H., Chen, Y.P., Ge, H.T., 2008. Potential impact of climate change on snow cover area in the Tarim River basin. Environmental Geology 53, 1465–1474.

Xu, Z.X., Chen, Y.N., Li, J.Y., 2004. Impact of climate change on water resources in the Tarim River basin. Water Resources Management 18 (5), 439–458.

Xu, Z.X., Li, J.Y., Liu, C.M., 2007. Long-term trend analysis for major climate variables in the Yellow River basin. Hydrological Processes 21, 1935–1948.

Xun, Y., Hu, Y., Ma, Y., 2001. The effecting to ecoenvironment of development of the lower river basin of Tarim and the countermeasure for rebuilt and rehabilitation this area. Arid Land Geology 24 (4), 342–345 [in Chinese].

Yue, S., Pilon, P., Phinney, B., 2003. Canadian streamflow trend detection: impacts of serial and cross-correlation. Hydrological Sciences Journal 48 (1), 51–63.

Zhang, H., Wu, J.W., Zheng, Q.H., Yu, Y.J., 2003. A preliminary study of oasis evolution in the Tarim Basin, Xinjiang, China. Journal of Arid Environments 55, 545–553.

Zhou, X., Li, C., 1990. The environment change of green corridor in the lower reach of Tarim River. In: Research on Resource, Environment and Remote Sensing in Tarim River. Scientific and Technology Press, Beijing, China, pp. 50–55 [in Chinese].

Zu, R.P., Gao, Q.Z., Qu, J.J., Qiang, M.R., 2003. Environmental changes of oases at southern margin of Tarim Basin, China. Environmental Geology 44, 639–644.