Quaternary International xxx (2013) 1–13

Contents lists available at ScienceDirect

Quaternary International

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

Changes in intra-annual runoff and its response to climate change and human activities in the headstream areas of the Tarim River Basin, China

Hongbo Ling [a,b], Hailiang Xu [a,b,*], Jinyi Fu [a,b]

[a] State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences (CAS), Urumqi 830011, China
[b] Laboratory of Environment Change in Arid Lands, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences (CAS), Urumqi 830011, China

ARTICLE INFO

Article history:
Available online xxx

ABSTRACT

Intra-annual runoff trends and periods in the headstream areas of the Tarim River Basin were investigated by non-parametric tests and wavelet analysis. The analysis was based on runoff data collected from six hydrological stations in the mountain headstreams and at the Alar station in the main stream of Tarim River Basin combined with the regional meteorological data collected from 1957 to 2008. The impacts of human activities and climate change on the runoff quantities during high-flow periods were investigated by structuring models. The results showed that (1) the runoff, air temperature and precipitation of the headstreams increased remarkably during both high-flow and low-flow periods. (2) In mountain headstreams, the concentration degree index (CDI) at the Xiehela hydrological station increased slightly, while the indexes at the other five stations (Shanliguilank, Kaqun, Yuzmenlek, Tongguzlek and Wuluwati) showed decreasing trends. (3) The CDIs of runoff in the mountain headstreams had significant periods of 3–8 years, which were similar to those of air temperature during high- and low-flow periods, but differed from those of precipitation. (4) Both climate change and human activities had significant effects on the total runoff of oasis headstreams during the period of 1993–2007, and climate change was a leading factor driving runoff evolution of oasis headstreams during high-flow periods. Overall, the results of this study provide a scientific basis for realizing reasonable allocation of water resources in the Tarim River Basin.

1. Introduction

Surface runoff is crucial to natural hydrological circles, being closely related to land cover (Rientjes et al., 2011) and a number of climatic factors, including precipitation, air temperature, and evaporation (Jiang et al., 2011; Jung and Chang, 2011; Yang and Yang, 2011; Zarghami et al., 2011; Li et al., 2011a). This is particularly true in arid and semi-arid regions, where runoff is primarily supplied by glacial melt water and rainfall in mountainous areas. The generation of surface runoff is more sensitive to the changes in climatic factors and areas of glacial and snow cover in arid and semi-arid regions (Gan, 2000; Chen et al., 2006; Xu et al., 2009). Global air temperature has risen by 0.74 C° in the last 100 years, increasing water circulation, spatial-temporal reallocation of water resources, and flood and drought hazards (IPCC, 2007). Many studies (Shi et al., 2007; Yang et al., 2008; Chen et al., 2010) have demonstrated that climate change has also occurred in the arid regions of northwest China. Furthermore, the rapid population change and unreasonable utilization of water resources have greatly restricted the economic growth and ecological conservation in these regions (Huo et al., 2007; Xiao et al., 2008). Accordingly, discussing the runoff processes of inland rivers under the background of global warming is necessary to realize sustainable utilization of water resources in arid regions of China.

The Tarim River Basin is the largest inland river basin in China, and is characterized by abundant natural resources within a fragile environment (Xu et al., 2011). Hydrologically, the Tarim River Basin is a closed catchment (Chen et al., 2006; Hao et al., 2008). The main stream of the Tarim River is a typical pure-dissipation inland river that does not yield water resources on its own, and is only supplied by runoff from precipitation and glacial melt water in the mountain headstreams (Hao et al., 2009; Xu et al., 2011). Therefore, the hydrological processes of this river basin are more typical than those

---

* Corresponding author. Laboratory of Environment Change in Arid Lands, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences (CAS), Urumqi 830011, China.
E-mail addresses: linghongbo0929@163.com (H. Ling), hufengxia0622@163.com (H. Xu).

1040-6182/$ – see front matter © 2013 Elsevier Ltd and INQUA. All rights reserved.
http://dx.doi.org/10.1016/j.quaint.2013.08.003

Please cite this article in press as: Ling, H., et al., Changes in intra-annual runoff and its response to climate change and human activities in the headstream areas of the Tarim River Basin, China, Quaternary International (2013), http://dx.doi.org/10.1016/j.quaint.2013.08.003

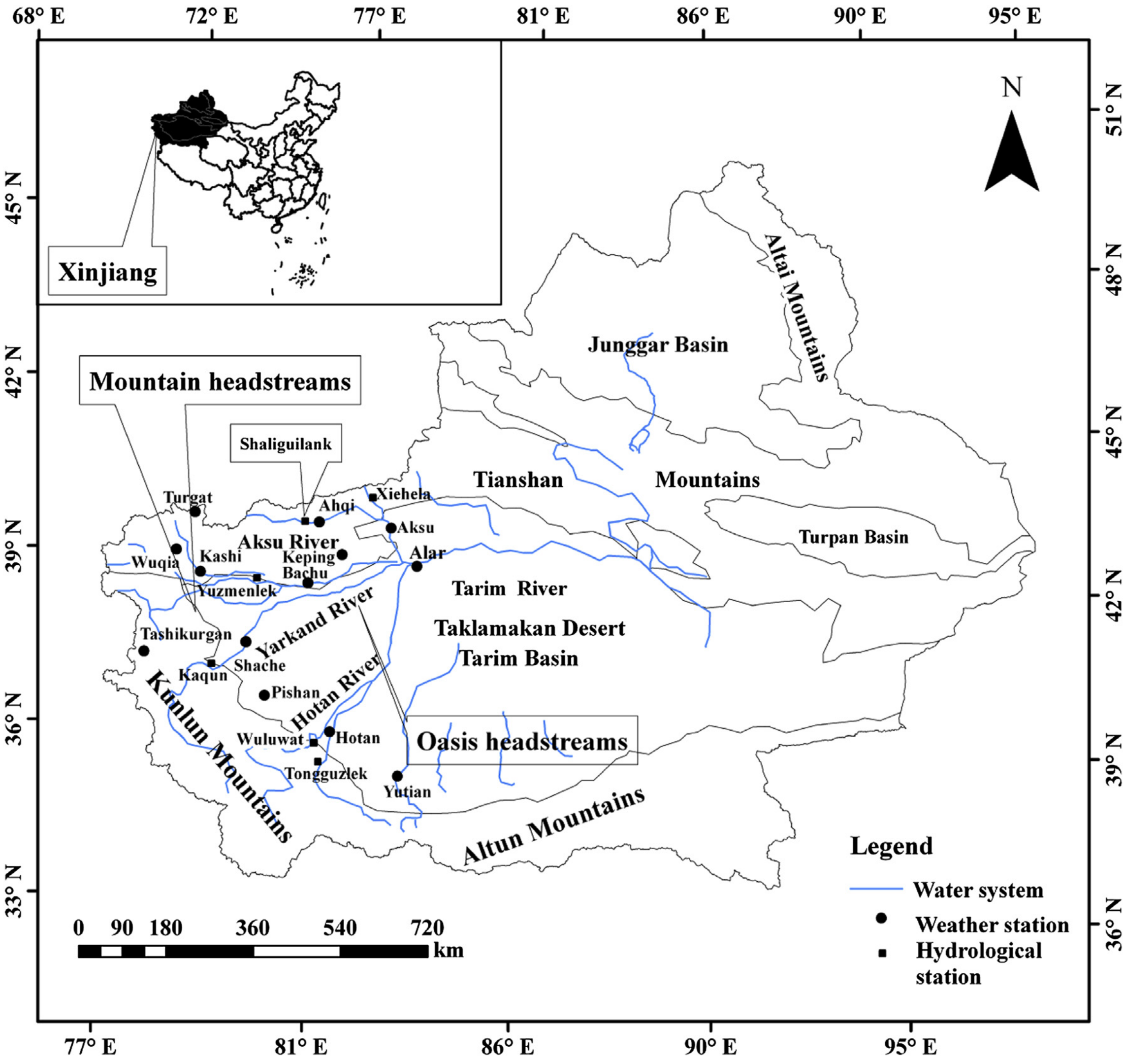

Fig. 1. The sketch map of the Tarim River Basin in Xinjiang.

of other regions in the middle and high latitudes of the Northern Hemisphere (Xu et al., 2011).

The population living in the Tarim River Basin increased from 360 × 10^4 in 1957 to 1043 × 10^4 in 2008. Additionally, the total arable area increased steadily from 70 × 10^4 ha in 1950 to 200 × 10^4 ha in 2008. Population growth, arable land expansion, and large-scale disordered water division in the high-flow period (from May to October) have led to a sharp reduction in the water quantity in the headstreams and main stream, drying over as much as 321 km of the river course in the downstream region, and large-scale death of *Populus euphratica* (Xu et al., 2008; Ye et al., 2010; Zhang et al., 2010). Therefore, deteriorating environmental conditions have been the major factor restricting economic growth and ecological conservation in the river basin. To reduce the competition between economic growth and ecological conservation for the available water resources, it is necessary to form a scientific basis for regulating and storing water resources. The regional flood and drought hazards also impact the intra-annual runoff patterns directly (Dai et al., 2008; Brocca et al., 2011). Therefore, it is important to characterise the intra-annual runoff change of the Tarim River headwaters. Studies of the runoff in the Tarim River Basin have to date mainly focused on their fractal patterns, trends, periodicity and abrupt changes (Xu et al., 2004, 2010, 2011; Chen et al., 2009; Zhang et al., 2010; Xu et al., 2011; Ling et al., 2013), but intra-annual runoff changes during the last 50 years have rarely been investigated. Therefore, this study analyzed monthly data pertaining to runoff, air temperature, and precipitation in the headstreams of the Tarim River Basin from 1957 to 2008. Discussion focused on the intra-annual runoff changes in headstreams and the correlation between the headstream runoff and the regional climate change based on the concentration degree index (CDI), non-parameter tests and wavelet analysis with the purpose of realizing reasonable allocation of water resources in the Tarim River headstreams.

Climate warming and human activities are the two primary factors impacting runoff change in the headstreams of the Tarim River Basin. A large number of studies (Xu et al., 2004; Chen et al., 2006; Liu et al., 2010; Fan et al., 2011; Xu et al., 2011) have demonstrated that runoffs from the Tarim River mountain headstreams are primarily influenced by climate factors (mainly air temperature and precipitation) rather than human activities. However, human activities greatly restrict runoff in the plain oasis areas of the headstreams and the main stream region (Hao et al., 2008; Tao et al., 2011). Previous studies (Hao et al., 2008; Tao et al., 2011) have separated the impacts of climate change and human activities on the total runoff of oasis headstreams in the Tarim River during the last 50 years, and considered the effects of anthropogenic activities to be stronger. However, in high-flow

Please cite this article in press as: Ling, H., et al., Changes in intra-annual runoff and its response to climate change and human activities in the headstream areas of the Tarim River Basin, China, Quaternary International (2013), http://dx.doi.org/10.1016/j.quaint.2013.08.003

period the impacts of climate change and human activities on runoff are more sensitive (Xu et al., 2006, 2007), and no studies have assessed the influences quantitatively. Therefore, runoff change data for the Tarim River headstreams during the high-flow period (May to October) was investigated. A correlation model of the total runoff in the Tarim River headstreams and the main stream was constructed, based on the abrupt-change years of climate change and the effects of human activities. Discussion considers the impacts of human activities and climate change on the total runoff of oasis headstreams to provide a theoretical basis for the reasonable utilization of water resources and coordinate economic growth in the river basin.

2. Data resources

Monthly runoff data were collected from six hydrological stations (Xiehela and Shaliguilanke in the Aksu River, Yuzmenlek and Kaqun in the Yarkand River, and Wuluwati and Tongguzlek in the Hotan River) in the mountain headstreams and the Alar station at the junction of the headstreams from 1957 to 2008 and were provided by the Tarim River Basin Administration. The part of the stream below the Alar station is the main stream of the Tarim River, while the part above this point is the headstream. Meteorological data were collected from 13 stations (i.e., Aksu, Alar, Ahqi, Bachu, Hotan, Keping, Kashi, Pishan, Shache, Tashikurgan, Turgat, Wuqia and Yutian) between 1960 and 2008. The hydrological and meteorological stations were distributed throughout the headstreams and are representative of the runoff and climate changes in the headstreams.

3. Study area

The Tarim River Basin is located in southern Xinjiang, China. Flowing through the Taklimakan Desert (the largest desert in China), the basin contains 144 rivers of nine river systems including the Aksu, Kashgar Yarkand, Hotan, Kongqi, Dina, Weigan-Kuche, Keriya and Qarqan rivers, with a total area of 102 × 10^4 km^2 (Chen et al., 2006). However, due to anthropogenic activities and climate change, the Qarqan, Keriya and Dina rivers stopped supplying water to the main stream before the 1940s, and the Kashgar, Kongqi and Weigan-Kuche rivers also lost their connection to the main stream of the Tarim River. Presently, only three drainage systems are connected to the Tarim River; the Aksu, Yarkand and Hotan rivers. These rivers are headstreams accounting for 73.2%, 3.6%, and 23.2% of the stream flow in the main stream of the river basin, respectively (Hao et al., 2009). The region is also characterized by scarce precipitation and intense evaporation owing to the closed interior geographical conditions. The river basin is flanked by the Altun, Kunlun and Tianshan Mountains in the south, west and north, respectively (Fig. 1). The mountainous areas of the Tarim River Basin store and provide water resources due to the accumulation of glaciers and snow, as well as via precipitation. The glaciers and snow meltwater account for 48.2% of the total river supplies, while precipitation and base flow account for 51.8%. With a length of 1321 km, the main stream of the Tarim River flows into Taitema Lake in the sink of the Tarim Basin. The average natural runoff volume in the Tarim River Basin is 398.3 × 10^8 m^3, and the volume of the underground water is 30.7 × 10^8 m^3; therefore, the total volume of the water resources is 429 × 10^8 m^3. The river basin has a continental arid desert climate with an annual temperature that varies from 10.6 °C to 11.5 °C and average annual average precipitation of 116.8 mm.

The regional natural vegetation is the desert riparian forest, in which *P. euphratica* Oliv. and Tamarix spp. are the main constructive species. The major herb species includes *Karelinia caspica*, *Poacynum hendersonii*, *Glycyrrhiza glabra*, and *Phragmites australis*.

4. Methods

In this study, the CDI was selected to illustrate the annual distribution features of runoff in the Tarim River Basin, nonparametric tests and wavelet analysis were used to detect the trend, abrupt change and period, and the periodicity–trend superposition model was applied to forecast the runoff quantity. The methods are described in detail below.

4.1. CDI

To reduce flood and drought disasters and achieve the optimal allocation of water resources in the Tarim River Basin, the concentration feature of annual runoff should be analyzed using the CDI. The CDI can indicate the concentration degree of annual runoff during the year and it reflects the uneven distribution characteristics of annual runoff over 12 months (Yang and Fan, 2010; Li et al., 2011b). The inter-regional value of the CDI is between 0 and 1. When the annual runoff is concentrated in a specific month, the CDI is 1, while when runoff within a year is evenly distributed between each month, the CDI is 0. The calculation process for the CDI has been previously described (Zhang and Qian, 2003).

Briefly, the monthly runoff is taken as the vector. The number of days in a year (365) can be regarded as a circle (360°), and 0.986° is roughly the angle corresponding to each day. The position of the runoff vector in January is zero, and the angle increases with an equal angle difference of 30° with each month (Table 1).

Table 1
Corresponding relation between angle and month

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Angle (%)	0	30	60	90	120	150	180	210	240	270	300	330

The equations used to calculate the CDI are:

$$R_y = \sum_{i=1}^{12} R(i) \sin\theta_i \tag{1}$$

$$R_x = \sum_{i=1}^{12} R(i) \cos\theta_i \tag{2}$$

The CDI (C_d) is defined as:

$$C_d = \sqrt{R_x^2 + R_y^2} \Big/ \sum_{i=1}^{12} R(i) \tag{3}$$

where i is the month, $R(i)$ is the mean value of runoff each month in a year and $\theta$is the angle indicated by the month (Li et al., 2011b).

4.2. Nonparametric test

A monotonic trend and an abrupt change are generally considered in hypothesis testing of a climate and runoff time series. Nonparametric tests can detect trends (Mann-Kendall monotonic trend test) and abrupt changes (Mann–Whitney abrupt-change test) without establishing the statistical distribution (e.g. normality and linearity) before conducting the test (Wang et al., 2008). Therefore, this method is superior to the *t*-test in testing capacity and is recommended for wide use by the World Meteorological Organization (Mitchell et al., 1966; Xu et al., 2011). In a nonparametric test, the null hypothesis implies that the trend or abrupt change of a time series is not significant, while the http://dict.cnki.net/dict_result.aspx?searchword=!(Da,I9X&tjType=sentence&style=&t=alternative+hypothesis">alternative hypothesis implies significant changes in the time series (Xu et al., 2006).

4.2.1. Mann-Kendall monotonic trend test

The time series ($X_1, X_2, X_3, \ldots, X_n$) are compared in turn, and the results are recorded as sgn(θ):

$$\mathrm{sgn}(\theta) = \begin{cases} 1, & \theta > 0 \\ 0, & \theta = 0 \\ -1, & \theta < 0 \end{cases}. \tag{4}$$

The Mann-Kendall statistic is calculated as:

$$s = \sum_{i=1}^{n-1} \sum_{k=i+1}^{n} \mathrm{sgn}(x_k - x_i), \tag{5}$$

where, x_k and x_i are random variables and n is the length of the selected data sequence. The test statistic Z_c is

$$Z_c = \begin{cases} \frac{s-1}{\sqrt{\mathrm{var}(s)}}, & s > 0 \\ 0, & s = 0 \\ \frac{s+1}{\sqrt{\mathrm{var}(s)}}, & s < 0 \end{cases}. \tag{6}$$

In this equation, when Zc is $-1.96 \le Zc \le 1.96$, the null hypothesis is accepted, which indicates that there is no obvious trend in the samples. The trend is significant at the 95% confidence level if $|Z|>1.96$ and at the 99% confidence level if $|Z|>2.58$. A positive Z_c indicates that the sequence has a rising trend, while a negative Z_c reflects a declining trend (Kendall, 1975).

4.2.2. Mann–Whitney abrupt-change test

Assuming that there is a time series $X = (X_1, X_2, \ldots, X_n)$ and its subsequences $Y = (X_1, X_2, \ldots, X_{n1})$ and $Z = (X_{n1+1}, X_{n1+2}, \ldots, X_{n1+n2})$, the Mann–Whitney abrupt-change test is calculated as:

$$Z_c = \frac{\sum_{t=1}^{n_1} r(x_t) - n_1(n_1 + n_2 + 1)/2}{\left[n_1 n_2 (n_1 + n_2 + 1)/12\right]^{1/2}}, \tag{7}$$

where $r(x_t)$ is the rank of the observed value, n_1 is the number of time series before the abrupt change and n_2 is the number of time series after the abrupt change, then $n_1+n_2 = n$. If $-Z_{1\text{ - }a/2} \le Z_c \le Z_{1\text{ - }a/2}$, the null hypothesis is accepted. $Z_{1\text{ - }a/2}$ is the quantile of the standard normal distribution of $1-a/2$ at the given test level of a (Xu et al., 2006).

4.3. Morlet continuous wavelet transform

A wavelet analysis is appropriate for determining the periodicity of a time series and analysis of the phase change and periodic intensity of a time series on different time scales (Farge, 1992; Ling et al., 2013). In wavelet analysis, the main periods have poor reliability if they are not subjected to a chi-square test at the 0.05 significance level (Torrence and Compo, 1998). Therefore, a significance test for the periodicity of the time series over the headstreams in the Tarim River Basin was conducted in this study by employing a chi-square test and detecting significant time sections from red-noise standard spectra (Torrence and Compo, 1998).

The Morlet wavelet (ψ_t) represents a wave modulated by a Gaussian function with the expression:

$$\psi(t) = \pi^{-1/4} e^{ict} e^{-t^2/2}, \tag{8}$$

where i is the unit of the imaginary number, t is the nondimensional time parameter, and c is a constant number (Farge, 1992; Torrence and Compo, 1998).

The continuous wavelet transform of a discrete signal $f(t)$ with a Morlet wavelet (ψ_t) is:

$$W_f(a,b) = \frac{1}{a} \int_R f(t) \psi^* \left(\frac{t-b}{a} \right) dt, \tag{9}$$

where $W_f\,(a,\,b)$ is the transform coefficient, a and b are a scale parameter and translation parameter, respectively, t is the time scale, and ψ^* is the complex conjugate.

The wavelet variance is used to determine the main periodicity on different scales of the time domain, and is expressed as

$$Var(a) = \int_{-\infty}^{+\infty} \left| W_f(a,b) \right|^2 db, \tag{10}$$

where, $Var(a)$ is the wavelet variance and a the time scale. The peak values of wavelet variance correspond to the main periods of different time scales (Torrence and Compo, 1998).

4.4. Periodicity-trend superposition model

Based on previous studies (Chen et al., 2006; Xu et al., 2006; Xu et al., 2010; Chen et al., 2011; Ling et al., 2013), the runoff in the Tarim River Basin has a significant trend and periodic change. Therefore, it is reasonable and feasible to use the periodicity–trend superposition model to predict the runoff quantity in this river basin.

The rationale and procedure are as follows (Chen et al., 2008; Ling et al., 2011a). First, the expectation value during the period $T + \tau$ is

$$\mu_{T+t} = a_T + b_\tau + \delta_{T+\tau}, \tag{11}$$

where, a_T is the mean, b_τ is the slope and $\delta_{T\,+\,\tau}$ is the increment for the period $T + \tau$.

Second, the temporal series data of at least two whole periods are needed; the data sample T must be a multiple of M, and $M \times N$ samples are used in the calculation. The temporal series data of the incomplete periods are used to update the prediction model and further improve its precision. N is the number of whole periods covered by the temporal series data; i.e., the time series data T are divided into N groups. The means of the first period and last period are obtained, and the initial slope ratio is estimated and the mean expectation value for temporal series $T = 0$ of the corresponding period is calculated using the respective equations:

$$\bar{b}_0 = (\bar{x}_N - \bar{x}_1)/(T - M), \tag{12}$$

$$\bar{a}_0 = x_1 - [\mathrm{int}(M/2) + 0.5]\bar{b}_0, \tag{13}$$

From the means of $\bar{a}_0$ and $\bar{b}_0$ during the period of the time series T, the increments during periods 1 to T are estimated according to $\bar{d}_t = x_t + \bar{a}_t$. The ratios are revised by subtracting the increments

Please cite this article in press as: Ling, H., et al., Changes in intra-annual runoff and its response to climate change and human activities in the headstream areas of the Tarim River Basin, China, Quaternary International (2013), http://dx.doi.org/10.1016/j.quaint.2013.08.003

from the means of ratios, $\widehat{d}_t = \overline{d}_1 - \overline{d}(t = 1, 2, \ldots, M)$, and assuming that $\widehat{a}_0 = \overline{a}_0$ and $\widehat{b}_0 = \overline{b}_0$; thus, the three parameters for periods 1 to T are estimated as follows:

$$\widehat{a}_t = \alpha\left(x_t - \widehat{d}_t\right) + (1-\alpha)\left(\widehat{a}_{t-1} + \widehat{b}_{t-1}\right), \tag{14}$$

$$\widehat{b}_t = \beta(\widehat{a}_t - \widehat{a}_{t-1})(1-\beta)\widehat{b}_{t-1}, \tag{15}$$

$$d_{1+M} = \gamma(x_t - \widehat{a}_t) + (1+\gamma)\widehat{b}_t. \tag{16}$$

The sum of increments for all periods should be zero; therefore, they must be standardized and the means should be obtained first:

$$v_i = \frac{1}{M}\sum_{i=1}^{M}\widehat{d}(j-1)M + i \quad (j = 2, 3, \ldots, n). \tag{17}$$

The increments are revised according to

$$d_{(j-1)M+i} = \widehat{d}_{(j-1)M+i} - v_i \ \ (j = 1, 2, \ldots, N+1; i = 1, 2, \ldots, M), \tag{18}$$

where, the parameters$\widehat{a}_T$, $\widehat{b}_T$ and $d_{T+\tau}$ (τ = 1, 2,..., M) in the superposition model are estimated, and the prediction model from period T to period τ is expressed as:

$$\widehat{x}_T(\tau) = \widehat{a}_T + \widehat{b}_T\tau + d_{T+\tau}. \tag{19}$$

Other data for the incomplete periods are used to update the prediction model:

$$\widehat{a}_{T+i} = \alpha(x_{T+i} - d_{T+i}) + (1-\alpha)\left(\widehat{a}_{T+i-1} + \widehat{b}_{T+i-1}\right), \tag{20}$$

$$\widehat{b}_{T+i} = \beta(\widehat{a}_{T+i} - \widehat{a}_{T+i-1}) + (1-\beta)\widehat{b}_{T+i-1} \quad (\mathrm{i} = 1, 2, \ldots, \mathrm{N}_1), \tag{21}$$

$$d_{T+M+i} = \gamma(x_{T+i} - \widehat{a}_{T+i}) + (1-\gamma)d_{T+i}. \tag{22}$$

The increments are revised according to:

$$d^*_{T+N_1+\tau} = d_{T+N_1+\tau} - d \quad (\tau = 1, 2, \ldots, M). \tag{23}$$

The prediction model of period $T + N_1$ to period τ in the future can be derived with the updated values:

$$\widehat{x}_{T+N_1}(\tau) = \widehat{a}_{T+N_1}\tau + d^*_{T+N_1+\tau} \quad (\tau = 1, 2, \ldots, M). \tag{24}$$

4.5. *Accumulative anomaly*

There is a time series $X = (X_1, X_2, \ldots, X_n)$ and accumulative anomaly subsequences $Y = (Y_1, Y_2, \ldots, Y_n)$, and the accumulative anomaly value (Y_i) is calculated using the equation (Hao et al., 2009):

$$Y_i = \sum_{i=1}^{n}(X_i - \overline{X}), \quad (i = 1, 2, 3, \ldots, n) \tag{25}$$

where n is the length of time series X, X_i is the ith vale of X, and $\overline{X}$is the mean value of X.

5. Results and analysis

5.1. *Annual change in characteristics of headstream runoff in the Tarim River Basin*

The total runoff in the mountain headstreams of the Tarim River Basin increased significantly in the last 50 years according to Chen et al. (2006), but the trends within the year of runoff in each mountain pass of the headstreams have rarely been reported. Therefore, this paper utilized the monthly runoff data pertaining to six mountain passes in the Tarim River mountain headstreams between 1957 and 2008 and analyzed the trends in different months by using the Mann–Kendall monotonic trend test.

As indicated in Table 2, at the Xiehela station on the Aksu River, runoff in April, June and September of between 1957 and 2008 were all below 1.96 ($Z_{0.05} = 1.96$), and thus the runoff in the three months increased insignificantly at the significance level of 0.05. The values for all other months were >1.96, indicating that runoff increased significantly during those months at the significance level of 0.05. Similarly, the Shaliguilank station (in the Aksu River) showed an unapparent increase in runoff in June, August, and September. However, significant increases were observed in the other months, especially in February, when the value was as high as 3.77 and the increase trend was most significant. The runoff of the Yarkand River between 1957 and 2008 did not increase significantly in April, July and September at the Kaqun station and in June and August at the Yuzmenlek station, and thus these two stations showed significant increase trends in the other months. For the Hotan River during the same study period, the runoff at the Wuluwati station increased insignificantly in June, decreased slightly in July, decreased significantly in August, and increased slightly in September. Runoff during all other months increased significantly at the significance level of 0.05. At the Tongguzlek station, the runoff trends did not differ significantly from April to

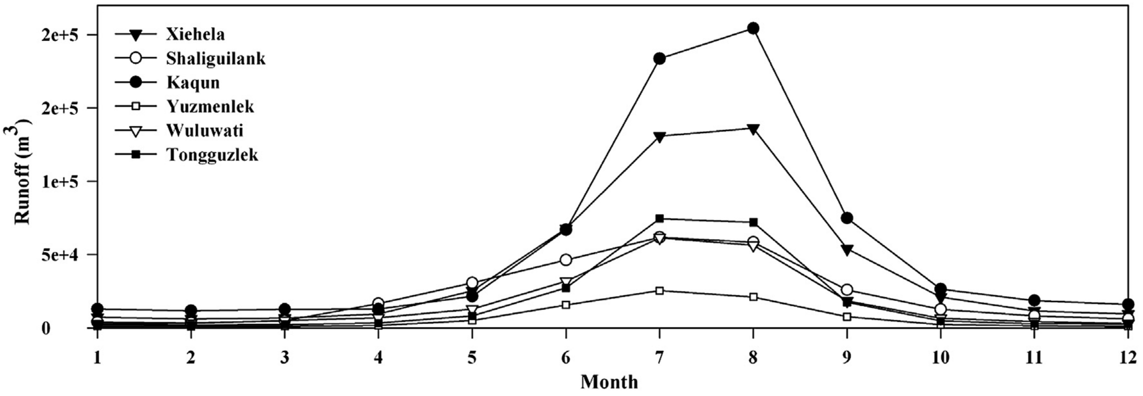

Fig. 2. Distribution of annual runoff of mountain headstreams in Tarim River Basin.

Please cite this article in press as: Ling, H., et al., Changes in intra-annual runoff and its response to climate change and human activities in the headstream areas of the Tarim River Basin, China, Quaternary International (2013), http://dx.doi.org/10.1016/j.quaint.2013.08.003

September between 1957 and 2008, while in the other months it presented a significant increase at the confidence level of 95%. From the above analysis, different stations in the Tarim River headstreams had different trends in runoffs. This was likely because the runoff trend was not only related to climate change, but also to geographical position, river supply, catchment area, and glaciers and snow patterns (Xu et al., 2006; Gao et al., 2010).

Table 2
The Mann-Kendall monotonic trend test of the monthly runoff in the mountain headstreams of Tarim River.

Month	Xiehela		Shaliguilanke		Kaqun		Yuzmenlek		Wuluwati		Tongguzlek	
	Z_c	H_0	Z_c	H_0	Z_c	H_0	Z_c	H_0	Z_c	H_0	Z_c	H_0
Jan	2.58	R	3.76	R	4.31	R	4.72	R	4.59	R	5.62	R
Feb	3.50	R	3.77	R	4.46	R	4.99	R	4.32	R	4.81	R
Mar	3.26	R	3.65	R	3.92	R	2.81	R	3.82	R	2.88	R
Apr	**1.06**	A	2.25	R	**1.78**	A	2.15	R	2.44	R	**1.01**	A
May	2.23	R	3.04	R	2.77	R	3.09	R	2.42	R	**1.18**	A
Jun	**1.66**	A	**1.87**	A	2.07	R	**1.91**	A	**1.35**	A	**0.99**	A
Jul	3.37	R	2.33	R	**1.33**	A	**1.33**	A	**−1.02**	A	**0.65**	A
Aug	2.94	R	**0.77**	A	**0.06**	A	**0.98**	A	−2.96	R	**−0.39**	A
Sep	**1.57**	A	**1.81**	A	**0.65**	A	2.34	R	**0.75**	A	**1.36**	A
Oct	2.49	R	2.68	R	2.79	R	3.48	R	3.62	R	2.61	R
Nov	3.28	R	2.50	R	3.86	R	4.55	R	4.46	R	3.78	R
Dec	2.77	R	3.54	R	3.81	R	4.51	R	4.92	R	4.20	R

Note: R-rejected, A-accepted. Significance level $\alpha = 0.05$.

Glacial meltwater and precipitation are the major sources of runoff of the mountain headstreams of the Tarim River. Therefore, the runoff is influenced by climate change (Xu et al., 2011). The runoff at different hydrological stations in the mountain headstreams was mainly concentrated from May to October between 1957 and 2008, when there was higher air temperature and more precipitation. Indeed, the runoff during these months accounted for 90% of the annual total runoff, so these months were regarded as the high-flow period, while the other 6 months belonged to the low-flow period (Fig. 2).

5.2. Concentration trend of intra-annual runoff in the Tarim River headstreams

The seasonal fluctuations of climate factors resulted in large differences in the allocation of intra-annual runoff in the mountain headstreams of the Tarim River (Fig. 2). Therefore, studying the monthly trend of runoff as well as the heterogeneity of intra-annual runoff change is meaningful for allocating water resources reasonably and regulating floods in the river basin scientifically. The CDI reflects the annual distribution characteristics of the river runoff well, so the index was combined with the Mann-Kendall monotonic trend test in this study to analyze trends of runoff CDI in the mountain headstreams of the Tarim River Basin between 1957 and 2008 (Table 3).

As shown in Table 3, in the mountain headstreams of the Tarim River, the CDI of intra-annual runoff did not change significantly at the Xiehela station between 1957 and 2008 ($Z_c = 1.82 < Z_{0.05} = 1.96$), but that at all other stations showed a decreasing trend. The CDI at the Wuluwati station was −4.24, followed by that at the Yuzmenlek station ($Z_c = -3.62$) and the Shaliguilank station ($Z_c = -2.64$). The CDI values of all three stations were below −2.58 ($-Z_{0.01} = -2.58$), indicating a significant decrease in intra-annual runoff at the confidence level of 99%. The decreasing trend at Tongguzlek was significant at the 0.05 level but this trend at the Kaqun station was not as strong. The CDI of runoff in the mountain headstreams is closely related to the annual inflow. To determine why spatial-temporal differences existed in the CDI at different hydrological stations in the mountain headstreams of the Tarim River, correlation models between inflow and the CDI of different stations in high- and low-flow periods were established (Table 4).

In the headstreams of the Tarim River, the CDI of each hydrological station was significantly correlated with the runoff during

Table 3
The Mann–Kendall monotonic trend test of CDI in the mountain headstreams of Tarim River.

Hydrological station	Mean value	Standard deviation	Coefficient of variation	Z_c	H_0	Trend
Xiehela	0.674	0.050	0.074	1.82	A	Increase slightly
Shaliguilank	0.598	0.048	0.080	−2.64	R	Decrease
Kaqun	0.654	0.046	0.070	−0.876	A	Decrease slightly
Yuzmenlek	0.708	0.029	0.041	−3.62	R	Decrease
Wuluwati	0.690	0.078	0.113	−4.24	R	Decrease
Tongguzlek	0.763	0.038	0.050	−2.02	R	Decrease

Note: R-rejected, A-accepted. Significance level $\alpha = 0.05$.

Table 4
Correlation model between CDI and different periods (high- and low-flow periods) runoff from 1957 to 2008

Hydrological station	Equation	R^2	F	P
Xiehela	$CDI = 0.0033H\text{-}0.372L+0.7181$	0.8148	107.7552	<0.0001
Shaliguilank	$CDI = 0.0016H\text{-}0.0094L+0.5995$	0.2421	7.8257	0.0011
Kaqun	$CDI = 0.0357H\text{-}0.2408L+0.6518$	0.8805	180.5707	<0.0001
Yuzmenlek	$CDI = 0.012H\text{-}0.1564L+0.7326$	0.5917	35.5027	<0.0001
Wuluwati	$CDI = 0.0031H\text{-}0.0076L+0.6511$	0.1277	3.5864	0.0352
Tongguzlek	$CDI = 0.0074H\text{-}0.076L+0.7267$	0.8904	178.7865	<0.0001

Note: *H*-High flow period, *L*-Low flow period, *CDI* -Concentration degree index.

Please cite this article in press as: Ling, H., et al., Changes in intra-annual runoff and its response to climate change and human activities in the headstream areas of the Tarim River Basin, China, Quaternary International (2013), http://dx.doi.org/10.1016/j.quaint.2013.08.003

high- and low-flow periods at the confidence level of 95% between 1957 and 2008, demonstrating that the runoff during these periods determined the trends in CDI. In fitting functions, six hydrological stations had negative fitting coefficients during the low-flow period, while positive ones appeared in the high-flow period. The runoff during the low-flow period slowed the annual CDI of runoffs, while that during the high-flow period accelerated the concentration. Nonetheless, the absolute values of equation fitting coefficients at the different stations were higher in the low-flow period (Xiehela: 0.372, Shaliguilank: 0.0094, Kaqun: 0.2408, Yuzmenlek: 0.1564, Wuluwati: 0.0076, Tongguzlek: 0.076) than the high-flow period (Xiehela: 0.0033, Shaliguilank: 0.0016, Kaqun: 0.0357, Yuzmenlek: 0.012, Wuluwati: 0.0031, Tongguzlek: 0.0074), which indicated that the contribution of the runoff in the low-flow period to the annual CDI was larger than that of the high-flow period. Accordingly, the runoff during the low-flow period was the leading factor resulting in the concentration of the intra-annual runoffs in the mountain headstreams. To further investigate the differences in CDI among different hydrological stations in the mountain headstreams, the intra-annual runoff trends at the stations during the high- and low-flow periods were analyzed.

As shown in Table 5, the runoff index in Xiehela in the high-flow period was higher than that in the low-flow period between 1957 and 2008, indicating that the increasing trend in runoff was stronger in the high-flow period compared with the low-flow period. Accordingly, the weaker increasing trend of the low-flow period reduced the mitigation of the CDI during the low-flow period, so the annual CDI of Xiehela presented an increasing trend (Table 3). For the other five hydrological stations, the runoff during high-flow periods had smaller CDI values than in the low-flow period, but the low-flow period determined the changes of CDI; therefore, the intensive increase in runoff in the low-flow period led to the downtrend in the CDI of runoffs (Table 3), and the intra-annual runoff allocations tended to be equalized.

In different catchments above hydrological stations for the headstream mountainous areas of the Tarim River Basin the mechanisms through which climate factors influence runoff processes differ due to different influencing factors including altitude, geographic location, terrain, glaciers, permafrost and snow area, etc. According to the existing data (Chen et al., 2009; Xu et al., 2009), air temperature in spring (from March to May) and summer (from June to August) rose insignificantly in the study region, while air temperature increased significantly during autumn (from September to November) and winter (from December to January) in the past 50 years (Xu et al., 2007, 2009). In addition, precipitation showed a significant increasing trend in summer, but no significant trends in any other seasons (Xu et al., 2007, 2009). At the Xiehela, Shaliguilank and Yuzmenlek stations, runoff is primarily supplied by snow melt water and rainfall (78% of the total runoff), which are most strongly influenced by summer precipitation and air temperature (Chen et al., 2009; Xu et al., 2009). Therefore, the runoff at those three hydrological stations in high- and low-flow periods had significant increasing trends (Table 5) as a consequence of the significant increases that occurred in summer precipitation and winter air temperature (Xu et al., 2009). In addition, when compared to Shaliguilank and Yuzmenlek, the CDI of the runoff at Xiehela showed an increasing trend (Table 3). This was because runoff during the high-flow period at Xihela was more strongly affected by the increasing summer precipitation due to the lower elevation than the other two stations (Xu et al., 2007, 2009). In Kaqun, Wuluwati and Tongguzlek, the runoff was primarily replenished by glacier melt water occupied 57%, and the runoff mainly was affected by the air temperature in summer (Chen et al., 2009; Xu et al., 2009). However, a slight increase in the summer air temperature could not cause the significant increase of runoff in high-flow periods. Additionally, as runoff of the low-flow period increased significantly (Table 5), and thus CDI of runoff in the three hydrological stations presented the significant decreasing trend (Table 3).

5.3. *Periodicity of concentration degree of headstream runoff in the Tarim River Basin*

Based on the CDI of runoff in the mountain headstreams of the Tarim River Basin between 1957 and 2008, the periods of the time series were obtained by the Morlet wavelet function (Fig. 3). When the wavelet variance is on the wave crest of the wavelet variance hydrograph and beyond the significant test hydrograph of 95%, the CDI of runoff has a significant period on the corresponding time scale. In the wavelet coefficients map, the positive phase indicates a wavelet coefficient over zero and higher runoff concentration degree, while the negative phase indicates a wavelet coefficient below zero and lower runoff concentration degree. Zero was the abrupt-change year, implying that an abrupt change occurred in the annual CDI of runoff.

As shown in Fig. 3, the significant periods of the Xiehela and Shaliguilank stations in the Aksu River were 7 years and 8 years, respectively, while those of the Yuzmenlek and Kaqun stations in Yarkand River and the Tonguzilek and Wuluwati stations in Hotan River were 6 years and 3 years, respectively. The significant periodicities of CDI at different stations are clearly illustrated in the wavelet coefficient map, and the positive and negative phases of each station presented a better periodic fluctuation in the corresponding significant period (Fig. 3). The changes in CDI were regular and alternative, and the periodicities were the results of mutual superposition or

Table 5
Runoff changes of high- and low- flow periods in the mountain headstreams of Tarim River Basin

Hydrological station	Period	Runoff (10^8 m^3)	Coefficient of variation	Z_c	H_0	Trend
Xiehela	High flow period	43.506	0.166	4.52	R	Increase
	Low flow period	5.074	0.229	2.53	R	Increase
Shaliguilank	High flow period	23.557	0.203	3.13	R	Increase
	Low flow period	4.308	0.587	3.73	R	Increase
Kaqun	High flow period	5.775	0.197	1.67	A	Increase slightly
	Low flow period	0.847	0.101	5.33	R	Increase
Yuzmenlek	High flow period	7.698	0.178	3.07	R	Increase
	Low flow period	0.747	0.254	4.70	R	Increase
Wuluwati	High flow period	18.774	0.239	−0.92	A	Decrease slightly
	Low flow period	2.519	1.041	4.54	R	Increase
Tongguzlek	High flow period	20.416	0.219	0.46	A	Increase slightly
	Low flow period	1.505	0.187	4.51	R	Increase

Note: R-rejected, A-accepted. Significance level $\alpha = 0.05$.

Please cite this article in press as: Ling, H., et al., Changes in intra-annual runoff and its response to climate change and human activities in the headstream areas of the Tarim River Basin, China, Quaternary International (2013), http://dx.doi.org/10.1016/j.quaint.2013.08.003

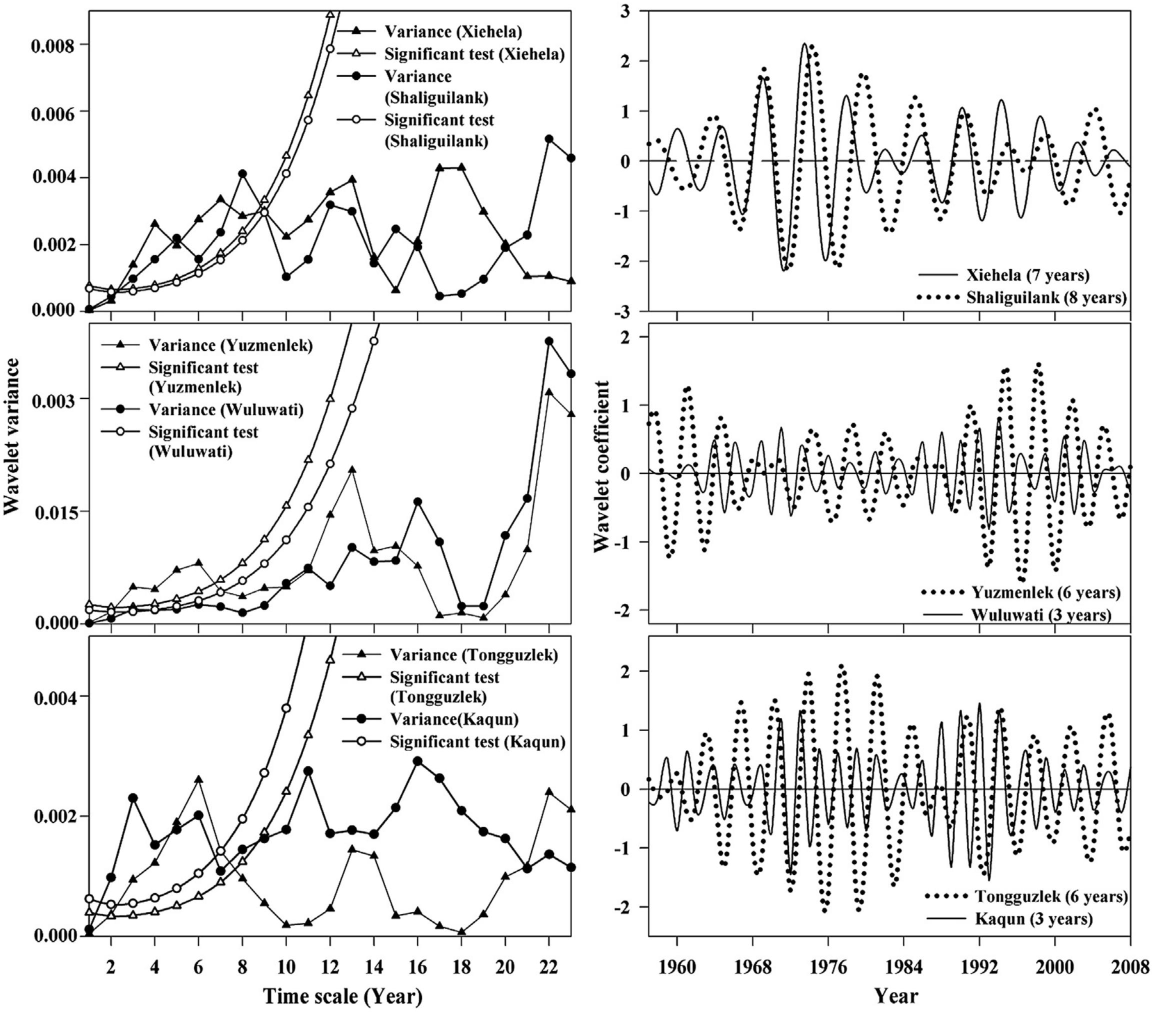

Fig. 3. Wavelet analysis of concentration degree index in the mountain headstreams of Tarim River Basin.

counteraction of different runoff periods in the mountain headstreams. According to the results, the CDI values of runoff in different areas are determined by the annual high- and low-flow changes in the mountain headstreams; therefore, changes in runoff of mountain headstreams in the high- and low-flow periods and its response to regional climate change are discussed herein.

5.4. Runoff changes during high- and low-flow periods in the Tarim River headstreams

The total annual runoff of six hydrological stations of mountain headstreams in the Tarim River Basin expressed a significant increasing trend (Chen et al., 2009). Similarly, the increasing trend of total runoff in the high-flow period (from May to October) was significant at the 0.05 level ($Z_c = 2.96 > Z_{0.05} = 1.96$) (Table 6). The trend in total runoff in the low-flow period (other 6 months within a year) increased more intensively than during the high-flow period with a Z_c of 4.92.

The runoff in the mountain headstreams of the Tarim River is mainly supplied by glacial melt water and precipitation, so changes in regional runoff are in response to climate change. Table 7 revealed the trends in air temperature and precipitation of high- and low-flow periods between 1960 and 2008. Air temperature presented a significant increase during two periods, similar to the trends in total runoff. Specifically, during the low-flow period, the Z_c of air temperature reached the maximum value of 4.72. Precipitation during the high-flow period increased significantly ($Z_c = 2.58$), but not during the low-flow period ($Z_c = 1.63 < Z_{0.05} = 1.96$). Therefore, the trends of runoff and climate factors (i.e., precipitation and air temperature) are consistent. In addition, previous studies (Xu et al., 2011; Ling et al., 2013) demonstrated that the correlation between air temperature and runoff is better than the correlation between precipitation and runoff. The relationship between air temperature and runoff helps to explain why the total runoff increase during the low-flow period was greater than that during the high-flow period (Table 6).

Table 6
Runoff trends of high- and low- flow periods in the mountain headstreams of Tarim River Basin.

Runoff	Time (year)	Mean value (10^8 m^3)	Coefficient of variation	Z_c	H_0	Trend
High flow period	1957–2008	119.69	0.133	2.96	R	Increase
Low flow period	1957–2008	15.00	0.393	4.92	R	Increase

Note: R-rejected, A-accepted. Significance level $\alpha = 0.05$.

Please cite this article in press as: Ling, H., et al., Changes in intra-annual runoff and its response to climate change and human activities in the headstream areas of the Tarim River Basin, China, Quaternary International (2013), http://dx.doi.org/10.1016/j.quaint.2013.08.003

Table 7
The Mann-Kendall monotonic trend test of climate factors in the headstreams of Tarim River.

Time section	Climate factors	Mean value	Coefficient of variation	Z_c	H_0	Trend
High flow period	Air temperature	18.02	0.025	2.20	R	Increase
	Precipitation	73.46	0.33	2.58	R	Increase
Low flow period	Air temperature	0.32	0.269	4.72	R	Increase
	Precipitation	19.18	0.44	1.63	R	Increase slightly

Note: R-rejected, A-accepted. Significance level $\alpha = 0.05$.

5.5. Periodicities of high- and low-flow periods of runoff in the Tarim River headstreams

Based on the wavelet analysis (Fig. 4), the total runoff of mountain headstreams in the high-flow periods between 1957 and 2008 showed a 17-year period, consistent with the total annual runoff (Chen et al., 2008). However, the period was not significant at the confidence level of 95%, when the significant period was 6 years. The total runoff of the low-flow period held a significant period of 4 years. In addition, the wavelet coefficient had a larger amplitude and stronger periodicity during the 1970s and after the 1990s.

The periodic changes in air temperature and precipitation in the high- and low-flow periods in the mountain headstreams of the Tarim River are shown in Fig. 5. The significant periods of air temperature in the high- and low-flow periods were 6 years and 4 years, respectively, which was the same as that for total runoff. However, the significant periods of precipitation were 8 years and 7 years during the high- and low-flow periods, respectively.

5.6. Impacts of climate change and human activities on the headstream runoff of the Tarim River Basin in high-flow period

Owing to anthropogenic and climatic changes in the headstreams over the last 50 years, further discussion of the impact of these factors is necessary to optimize the management of water resources in the Tarim River Basin. For this reason, this paper selected the high-flow period (from May to October) to separate the impacts of human activities and climate change on the total runoff in the oasis headstreams.

5.6.1. Determination of the abrupt-change year of human activities impacting headstream runoff in the high-flow period

According to the calculations, the runoff of evaporation and precipitation supplies in the oasis headstreams of Tarim River Basin accounted for 0.05% of the total runoff, so the impact of climate change on the runoff was extremely weak. Then, inter-regional water consumption increases with greater human activity, and can reflect the intensity of human activity (Zhou et al., 2012). To determine the year when human activities began to impact the total runoff of oasis headstreams, the abrupt-change year of inter-

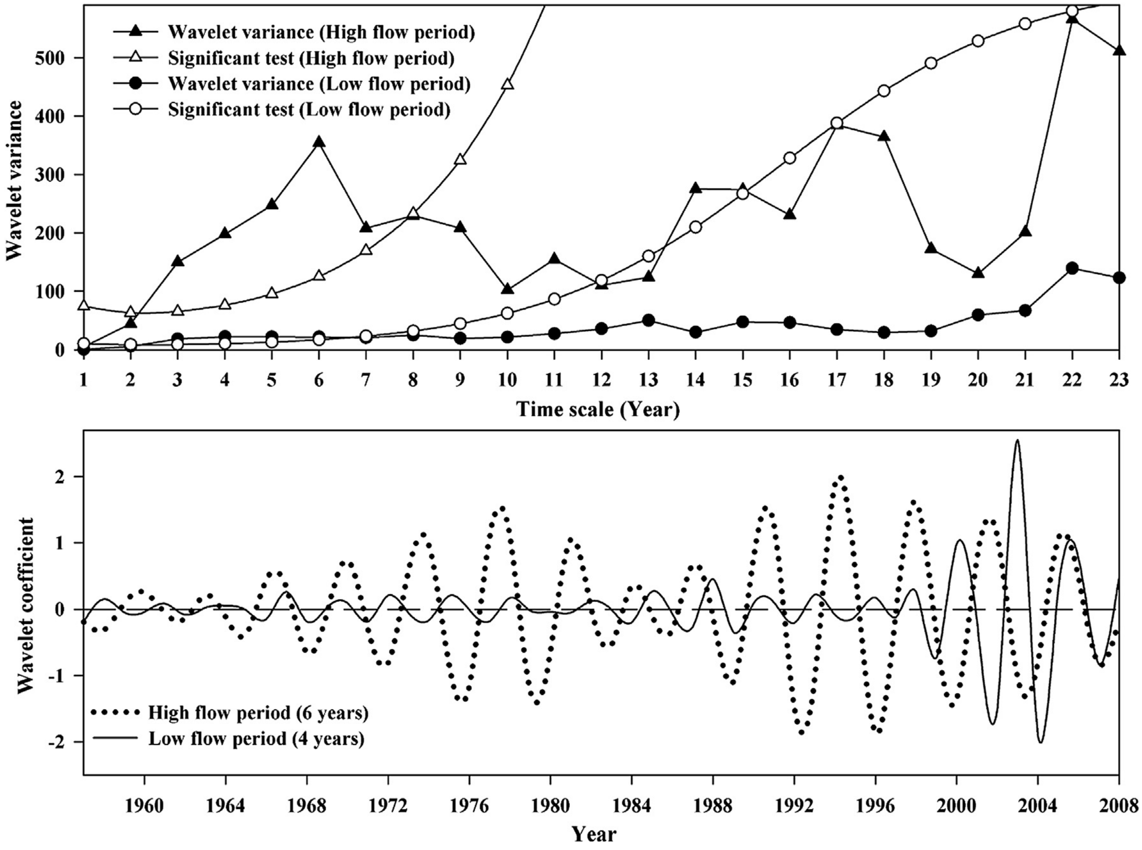

Fig. 4. Wavelet analysis of runoff for high- and low- flow periods in the mountain headstreams of Tarim River Basin.

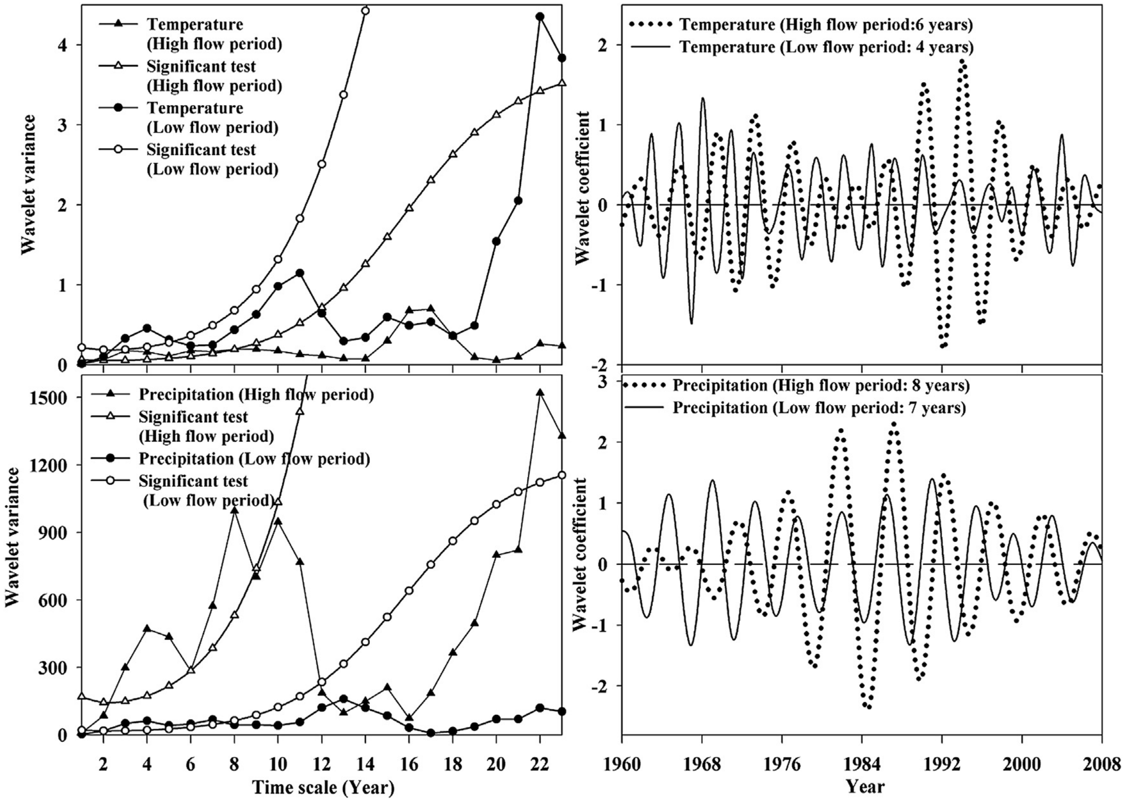

Fig. 5. Wavelet analysis of climate factors for high- and low- flow periods in the mountain headstreams of Tarim River Basin.

regional water consumption was considered to be when human activities began to severely impact the regional runoff (Zhou et al., 2012). In this study, the inter-regional water consumption of the oasis headstreams was regarded as the difference between the total runoff of headstream mountainous areas and runoff at the Alar station for analysis of the intensity of human activities.

Fig. 6 describes the accumulative anomalies of inter-regional water consumption and total runoff in the mountain headstreams during the high-flow period between 1957 and 2008. The accumulative anomaly of inter-regional water consumption had a fluctuating declining trend in 1993 and increased rapidly after 1993, which implied that 1993 was the beginning of water consumption aggravation in the oasis headstreams. Similarly, an abrupt increase also occurred in total runoff of the mountain headstreams in the high-flow period in 1993. Ling et al. (2011b) found that air temperature and precipitation increased abruptly in 1993 and 1992, respectively, in the headstream mountainous areas of this river basin. As annual runoff is more sensitive to air temperature than precipitation (Xu et al., 2011), the abrupt change in annual runoff in 1993 is consistent with the concurrent abrupt increase in air temperature (Ling et al., 2013). Moreover, precipitation in the mountain areas exists in solid form, and runoff from this can have a time lag and may appear in the following year owing to melting precipitation (Ling et al., 2013). Therefore, the abrupt change of precipitation appeared earlier than that of annual runoff in the Tarim River Basin. The year 1993 can be regarded as the point at which climate change began impacting runoff in the mountain headstreams (Xu et al., 2011; Ling et al., 2013). A Mann–Whitney abrupt-change test was utilized to further investigate the significance of abrupt changes in inter-regional water consumption and total runoff of mountain headstreams in the high-flow period of the Tarim River (Table 8).

Table 8
Mann–Whitney abrupt change test of interval water consumption and total runoff of mountain headstreams in the Tarim River Basin.

High flow period	Time sections	Mean value(10^8 m^3)	Coefficient of variation	Z_c	H_0
Interval water consumption	1957–1993	114.404	0.121	3.79	R
	1994–2008	132.713	0.098		
Total runoff of mountain headstreams	1957–1993	78.104	0.100	4.62	R
	1994–2008	93.496	0.089		

Note: R-rejected, A-accepted. Significance level $\alpha = 0.05$.

The Mann–Whitney abrupt test (Table 8) produced inter-regional water consumption and total runoff values for mountain headstreams of 3.79 and 4.62, which were both over 1.96 ($Z_{0.05} = 1.96$); thus, the null hypothesis was rejected at the significance level of 0.05. These findings indicated that 1993 was not only the beginning of the significant impact of climate change on the total runoff in the mountain headstreams during the high-flow period, but also the point at which anthropogenic activities began to have a significant impact on the total runoff of oasis headstreams. Consequently, the impacts of climate change and

Please cite this article in press as: Ling, H., et al., Changes in intra-annual runoff and its response to climate change and human activities in the headstream areas of the Tarim River Basin, China, Quaternary International (2013), http://dx.doi.org/10.1016/j.quaint.2013.08.003

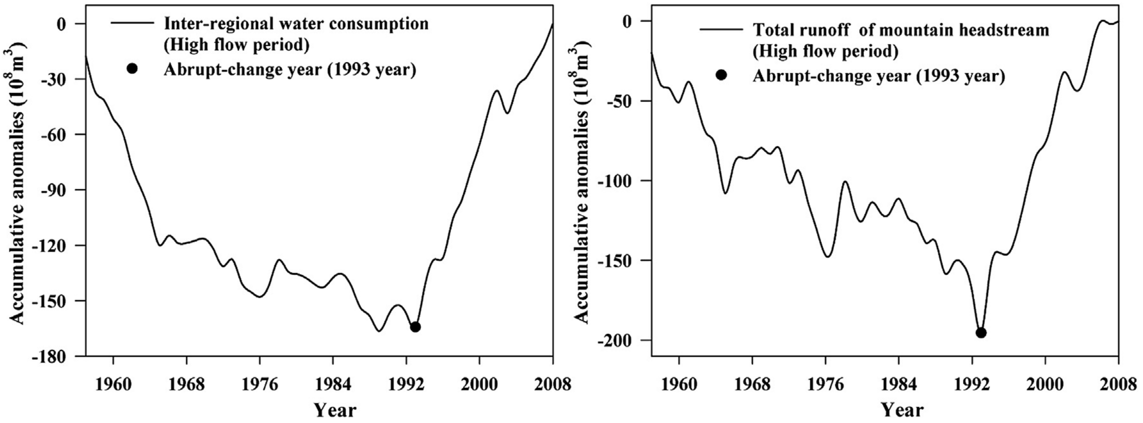

Fig. 6. Accumulative anomalies of inter-regional water consumption and total runoff of mountain headstreams in high flow period of Tarim River Basin.

anthropogenic activities on the total runoff of headstreams in the high-flow period were significant after 1993.

5.6.2. Models for the impacts of climate change and human activities on total runoff of headstream oases in the high-flow period

In this study, 1993 was taken as the abrupt-change year for the effects of climate change and human activities on total runoff in the high-flow period of the Tarim River headstream areas. Subsequently, models were built to distinguish between the impacts of climate change and human activities on the total runoff during high-flow period. The detailed steps were as follows: First, the runoff after 1993 was predicted based on the runoff at the Alar hydrological station during the high-flow period (the station between the headstream and the main stream) before 1993. Due to weak climate change and human activities during the high-flow period before 1993, the runoff in the high-flow period at the Alar station before 1993 was taken as the reference value, while the runoff after 1993 attained by modeling was considered to be natural runoff that was less influenced by human activities and climate change ($R_{\mathrm{HC\ (sli)}}$). Second, the total runoff in the mountain headstreams during the high-flow period was mainly impacted by climatic factors. Considering that climate change started to impact the total runoff of mountain headstreams severely in 1993, the correlation between the two models was established based on the total runoff of the mountain headstreams and the runoff at the Alar station during the high-flow period before 1993. The runoff at the Alar station impacted by climate change after 1993 was calculated by a correlation model based on the total runoff of the mountain headstreams in the high-flow period after 1993 ($R_{\mathrm{C(str)}}$). The measured runoff at the Alar station during the high-flow period after 1993 was recorded as R_{M}. The functions calculating the impacts of climate change and human activities on the headstream runoff in the high-flow period were as follows:

$$\text{Impact of climate change}: \Delta R_{\mathrm{C}} = R_{\mathrm{C(str)}} - R_{\mathrm{HC(sli)}} \tag{26}$$

$$\text{Impact of human activites}: \Delta R_{\mathrm{H}} = R_{\mathrm{C(str)}} - R_{\mathrm{M}} \tag{27}$$

Chen et al. (2011) showed that tendency and periodicity existed in the runoff at the Alar station, so the periodic superposition trend model was utilized to predict the runoff at that location during the high-flow period after 1993. Wavelet analysis indicated that the runoff in the high-flow period at the Alar station had periodic changes of 6-years and 17-years from 1957 to 1993. Considering the predictable length and accuracy, this study took a 17-year period as the calculation base. The runoff during the high-flow period at the Alar station during 1957–1993 was then input into the model, and the following parameters were obtained: periodic mean smoothing parameter $\alpha = 0.01000000$, periodic slope smoothing parameter $\beta = 0.01000000$, periodic increment smoothing parameter $\gamma = 0.01000000$. The structured model is shown in Table 9.

Table 9
Fitted equation of runoff in Alar station in the high flow period.

Runoff (Alar)	Time (year)	Period (year)	Mean value(10^8 m^3)	Slope	Prediction model	Average relative error
High flow period	1957–1993	17	33.076	−0.213	$X(\tau) = 33.076\text{-}0.213\tau + d_{t+\tau}$	6.28%

Note: $X(\tau)$ is the prediction result, τ is the period, and $d_{t+\tau}$ is the periodic increment and decrement.

As shown in Table 9, the mean relative error of the function was 6.28% from 1957 to 1993, and the fitting result is accurate. Accordingly, the above function was utilized to calculate $R_{\mathrm{HC(sli)}}$ in periods after 1993 (1994–2007) (Fig. 7).

Subsequently, the correlation model of $R_{\mathrm{C\ (str)}}$ was constructed as follows based on the runoff data of the mountain headstreams and at the Alar station in the high-flow period during 1957–1993.

$$\mathrm{AR} = 572.7941 - 0.3058Y + 0.5889\mathrm{HR}, R^2 = 0.83 \tag{28}$$

where, AR is the runoff in Alar in the high-flow period, HR is the total runoff of the mountain headstreams during the high-flow period, and Y is the year. Therefore, the $R_{\mathrm{C\ (str)}}$ (i.e., AR) after 1993 was calculated in terms of equation (28) based on the measured runoff data (i.e., HR) of the mountain headstreams in the high-flow period during 1994–2007 (Fig. 7).

5.6.3. Separation of effects of climate change and human activities on total runoff of headstream oases in the high-flow period

The impacts of both climate change and human activities were calculated by functions (26, 27) to separate the impacts of climate change and human activities on the total runoff of oasis headstreams in the high-flow period (Table 10).

Please cite this article in press as: Ling, H., et al., Changes in intra-annual runoff and its response to climate change and human activities in the headstream areas of the Tarim River Basin, China, Quaternary International (2013), http://dx.doi.org/10.1016/j.quaint.2013.08.003

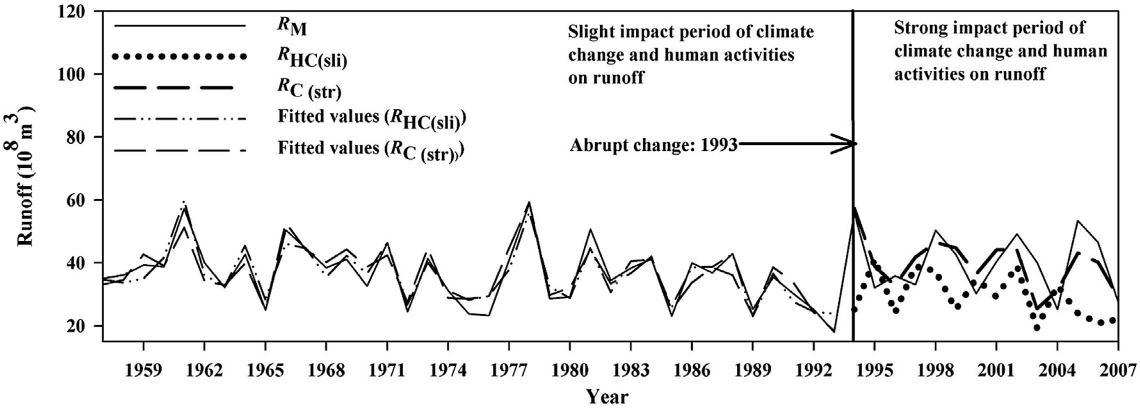

Fig. 7. Predicted values of $R_{C\ (str)}$ and $R_{HC(sli)}$ in the high flow period of Tarim River Basin.

Table 10
Affected quantities of climate change and human activities in the oasis headstream of Tarim River Basin.

Runoff	Time (year)	$R_{C(str)}$ (10^8 m^3)	$R_{HC(sli)}$ (10^8 m^3)	R_M (10^8 m^3)	Affected quantity of climate change		Affected quantity of human activities	
					ΔR_C(10^8 m^3)	$\Delta R_C/R_{C(str)}$(%)	ΔR_H(10^8 m^3)	$\Delta R_H/R_{C(str)}$(%)
High flow period	1994–1999	261.914	191.797	249.874	70.117	26.77	−12.040	−4.60
	2000–2007	293.523	222.292	312.35	71.231	24.27	18.827	6.41

In terms of interdecadal variation during the high-flow period (Table 10), the total runoff in the oasis headstreams increased by 70.117 × 10^8 m^3 owing to climate change, but decreased by 12.04 × 10^8 m^3 in response to anthropogenic activities from 1994 to 1999. Between 2000 and 2007, both climate change and human activities in the high-flow period led to an increase in runoff of 90.058 × 10^8 m^3 in the oasis headstreams. From the specific values of the effect of climate change on quantity (ΔR_C) and human activities on quantity (ΔR_H) to the theoretical runoff at the Alar station under the background of climate change ($R_{C(str)}$), climate change had a relatively stronger impact on the total runoff of oasis headstreams than human activities between 1994 to 1999 and 2000 to 2007. Accordingly, climate change is the leading factor of changes in runoff during the high-flow period in the oasis headstreams of the Tarim River Basin. Particularly, the total runoff of oasis headstreams in the high-flow period from 1994 to 1999 was reduced by human activities, which increased the runoff by 18.827 × 10^8 m^3 in the high-flow period from 2000 to 2007. This reason was as follows: to satisfy the ecological and agricultural water use demands in the main stream of the Tarim River in the high-flow period (from May to October), water managers regulated the runoff in the low-flow period by implementing headstream water conservation projects, and part of the water was stored during the low-flow period and supplied to the main stream through the Alar station in the high-flow period after 2000. The finding indicates that human activities have altered the temporal-spatial distributions of water resources in the Tarim River Basin, and scientific management would accelerate high-efficiency and reasonable utilization of water resources.

6. Conclusions

The annual changes in runoff and the impact factors of runoff changes in the headstreams of the Tarim River were analyzed based on climate and runoff data from the last 50 years. The conclusions were as follows:

1. The monthly runoff trends at each hydrological station in the mountain headstreams were different and presented an overall increase. The runoff concentrated between May and October, when temperatures were warmer. Furthermore, the total runoff, air temperature and precipitation in the headstreams all increased remarkably in both high- and low-flow periods, and the increasing trend was stronger in the low-flow periods than in the high-flow periods.
2. The CDI of runoff in the mountain headstreams increased slightly at the Xiehela station and decreased at the other stations. CDI changes were restricted by changes in runoff during high- and low-flow periods, but were more closely related to changes in runoff during the low-flow period.
3. The CDI of runoff had significant periods of 7 years and 8 years at the Xiehela and Shaliguilank stations, 6 years at the Yuzmenlek and Tongguzlek stations, and 3 years at the Wuluwati and Kaqun stations. Significant 6-year periods appeared in both runoff and air temperature during the high-flow period, and their significant period was 4 years in the low-flow period. Precipitation showed significant periods of 8 and 7 years in the high- and low-flow periods, respectively.
4. After 1993, climate change and human activities had a significant impact on the total runoff of the oasis headstreams during the high-flow period. Climate change was found to be the leading factor driving changes in runoff in the high-flow period in oasis headstreams. However, appropriately regulating the disturbance of water resources by anthropogenic activities is also essential to the optimization of water resources allocation.

Acknowledgements

This work was supported by National Natural Science Foundation of China (41171427 and 41001066), the National Basic Research Program of China (Program 973) (2009CB421308) and Ministry of Water Resources' Special Funds for Scientific Research on Public Causes (201101049).

Please cite this article in press as: Ling, H., et al., Changes in intra-annual runoff and its response to climate change and human activities in the headstream areas of the Tarim River Basin, China, Quaternary International (2013), http://dx.doi.org/10.1016/j.quaint.2013.08.003

References

Brocca, L., Melone, F., Moramarco, T., 2011. Distributed rainfall-runoff modelling for flood frequency estimation and flood forecasting. Hydrological Processes 25, 2801–2813.

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., Pang, Z.H., Hao, X.M., Xu, C.C., Chen, Y.P., 2008. Periodic changes of stream flow in the last 40 years in Tarim River Basin, Xinjiang, China. Hydrological Processes 22, 4214–4221.

Chen, Y.N., Xu, C.C., Hao, X.M., Li, W.H., Chen, Y.P., Zhu, C.G., 2009. Fifty-year climate change and its effect on annual runoff in the Tarim River Basin, China. Quaternary International 208, 53–61.

Chen, S.Y., Shi, Y.Y., Guo, Y.Z., Zheng, Y.X., 2010. Temporal and spatial variation of annual mean air temperature in arid and semiarid region in northwest China over a recent 46 year period. Journal of Arid Land 2, 87–97.

Chen, Z.S., Chen, Y.N., Xu, C.C., 2011. Change trend and prediction of annual runoff in mainstream area of the Tarim River in recent 50 years. Arid Land Geography 34, 44–51 (in Chinese).

Dai, Z.J., Du, J.Z., Li, J.F., Li, W.H., Chen, J.Y., 2008. Runoff characteristics of the Changjiang River during 2006: effect of extreme drought and the impounding of the Three Gorges Dam. Geophysical Research Letters 35, L07406.

Fan, Y.T., Chen, Y.N., Li, W.H., Wang, H.J., Li, X.G., 2011. Impacts of temperature and precipitation on runoff in the Tarim River during the past 50 years. Journal of Arid Land 3, 220–230.

Farge, M., 1992. Wavelet transforms and their applications to turbulence. Annual Review of Fluid Mechanics 24, 395–457.

Gan, T.Y., 2000. Reducing vulnerability of water resources of Canadian Prairies to potential droughts and possible climate warming. Water Resources Management 14, 111–135.

Gao, X., Ye, B.S., Zhang, S.Q., Qiao, C.J., Zhang, X.W., 2010. Glacier runoff variation and its influence on river runoff during 1961–2006 in the Tarim River Basin, China. Science China-earth Sciences 53, 880–891.

Hao, X.M., Chen, Y.N., Xu, C.C., Li, W.H., 2008. Impacts of climate change and human activities on the surface runoff in the Tarim River basin over the last fifty years. Water Resources Management 22, 1159–1171.

Hao, X.M., Chen, Y.N., Li, W.H., 2009. Impact of anthropogenic activities on the hydrologic characters of the mainstream of the Tarim River in Xinjiang during the past 50 years. Environmental Geology 57, 435–445.

Huo, Z.L., Feng, S.Y., Kang, S.Z., Dai, X.Q., Li, W.C., Chen, S.J., 2007. The response of water-land environment to human activities in arid Minqin oasis, northwest China. Arid Land Research and Management 21, 21–36.

IPCC Report, 2007. Climate Change 2007: Report of Working Group of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 16–72.

Jiang, S.H., Ren, L.L., Yong, B., Sing, V.P., Yang, X.L., Yuan, F., 2011. Quantifying the effects of climate variability and human activities on runoff from the Laohahe basin in northern China using three different methods. Hydrological Processes 25, 2492–2505.

Jung, I.W., Chang, H.J., 2011. Assessment of future runoff trends under multiple climate change scenarios in the Willamette River Basin, Oregon, USA. Hydrological Processes 25, 258–277.

Kendall, M.G., 1975. Rank Correlation Methods. Charles Griffin, London, pp. 10–35.

Li, X.M., Li, L.H., Guo, L.P., Zhang, F.Y., Adsavakulchai, S., Shang, M., 2011a. Impact of climate factors on runoff in the Kaidu River watershed: path analysis of 50-year data. Journal of Arid Land 3, 132–140.

Li, X.M., Jiang, F.Q., Li, L.H., Wang, G.Q., 2011b. Spatial and temporal variability of precipitation concentration index, concentration degree and concentration period in Xinjiang, China. International Journal of Climatology 31, 1679–1693.

Ling, H.B., Xu, H.L., Shi, W., Zhang, Q.Q., 2011a. Regional climate change and its effects on the runoff of Manas River, Xinjiang, China. Environmental Earth Sciences 64, 2203–2213.

Ling, H.B., Xu, H.L., Zhang, Q.Q., Shi, W., 2011b. The multi-time scale analysis on climate change and runoff processes in the Tianshan Mountains, Xinjiang. Journal of Natural Resources 26, 1908–1917 (in Chinese).

Ling, H.B., Xu, H.L., Fu, J.Y., 2013. High- and low-flow variations in annual runoff and their response to climate change in the headstreams of the Tarim River, Xinjiang, China. Hydrological Processes 27, 975–988.

Liu, Z.F., Xu, Z.X., Huang, J.X., Charles, S.P., Fu, G.B., 2010. Impacts of climate change on hydrological processes in the headwater catchment of the Tarim River basin, China. Hydrological Processes 24, 196–208.

Mitchell, J.M., Dzerdzeevskii, B., Flohn, H., Hofmeyr, W.L., Lamb, H.H., Rao, K.N., Walle'n, C.C., 1966. Climate Change, WMO Technical Note No. 79. World Meteorological Organization, Geneva.

Rientjes, T.H.M., Haile, A.T., Kebede, E., Mannaerts, C.M.M., Habib, E., Steenhuis, T.S., 2011. Change in land cover, rainfall and stream flow in Upper Gilgel Abbay catchment, Blue Nile basin-Ethiopia. Hydrology and Earth System Sciences 15, 1979–1989.

Shi, Y.F., Shen, Y.P., Kang, E.S., Li, D.L., Ding, Y.J., Zhang, G.W., Hu, R.J., 2007. Recent and future climate change in northwest China. Climatic Change 80, 379–393.

Tao, H., Gemmer, M.L., Bai, Y.G., Su, B.D., Mao, W.Y., 2011. Trends of streamflow in the Tarim River Basin during the past 50 years: human impact or climate change? Journal of Hydrology 400, 1–9.

Torrence, C., Compo, G.P., 1998. A practical guide to wavelet analysis. Bulletin of the American Meteorological Society 79, 61–78.

Wang, W., Chen, X., Shi, P., vanGelder, P.H.A.J.M., 2008. Detecting changes in extreme precipitation and extreme streamflow in the Dongjiang River Basin in southern China. Hydrology and Earth System Science 12, 207–221.

Xiao, S.C., Li, J.X., Xiao, H.L., Liu, F.M., 2008. Comprehensive assessment of water security for inland watersheds in the Hexi Corridor, Northwest China. Environmental Geology 55, 369–376.

Xu, C.C., Chen, Y.N., Li, W.H., Chen, Y.P., 2006. Climate change and hydrologic process response in the Tarim River Basin over the past 50 years. Chinese Science Bulletin 51, 125–136.

Xu, C.C., Chen, Y.N., Li, W.H., Chen, Y.P., 2007. Climate change and its impact on snow cover area in the Tarim River Basin over the last 45 years. Journal of Glaciology and Geocryology 29, 183–190 (in Chinese).

Xu, C.C., Chen, Y.N., Hamid, Y., Tashpolat, T.Y., Chen, Y.P., Ge, H.T., 2009. Long-term change of seasonal snow cover and its effects on river runoff in the Tarim River basin, northwestern China. Hydrological Processes 23, 2045–2055.

Xu, J.H., Li, W.H., Ji, M.H., Lu, F., Dong, S., 2010. A comprehensive approach to characterization of the nonlinearity of runoff in the headwaters of the Tarim River, western China. Hydrological Processes 24, 136–146.

Xu, 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.

Xu, H.L., Zhou, B., Song, Y.D., 2011. Impacts of climate change on headstream runoff in the Tarim River Basin. Hydrology Research 42, 20–29.

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, 439–458.

Yang, H.B., Yang, D.W., 2011. Derivation of climate elasticity of runoff to assess the effects of climate change on annual runoff. Water Resources Research 47, W07526.

Yang, J.H., Ren, C.Y., Jiang, Z.H., 2008. Characteristics of extreme temperature event and its response to regional warming in Northwest China in past 45 years. Chinese Geographical Science 18, 70–76.

Yang, M.L., Fan, X.M., 2010. Analysis on the variations of annual runoff distribution in the Weihe Basin. Meteorological and Environmental Research 1, 91–94.

Ye, Z.X., Chen, Y.N., Li, W.H., 2010. Ecological water demand of natural vegetation in the lower Tarim River. Journal of Geographical Sciences 20, 261–272.

Zarghami, M., Abdi, A., Babaeian, I., Hassanzadeh, Y., Kanani, R., 2011. Impacts of climate change on runoffs in East Azerbaijan, Iran. Global and Planetary Change 78, 137–146.

Zhang, J.B., Wu, G.H., Wang, Q.M., Li, X.Y., 2010. Restoring environmental flows and improving riparian ecosystem of Tarim River. Journal of Arid Land 2, 43–50.

Zhang, L.J., Qian, Y.F., 2003. Annual distribution features of precipitation in China and their interannual variations. Acta Meteorological Sinica 17, 146–163.

Zhang, Q., Xu, C.Y., Tao, H., Jiang, T., Chen, Y.D., 2010. Climate changes and their impacts on water resources in the arid regions, a case study of the Tarim River basin, China. Stochastic Environmental Research and Risk Assessment 24, 349–358.

Zhou, H.Y., Zhang, X.L., Xu, H.L., Ling, H.B., Yu, P.J., 2012. Influences of climate change and human activities on Tarim River runoffs in China over the past half century. Environmental Earth Sciences 67, 231–241.

Please cite this article in press as: Ling, H., et al., Changes in intra-annual runoff and its response to climate change and human activities in the headstream areas of the Tarim River Basin, China, Quaternary International (2013), http://dx.doi.org/10.1016/j.quaint.2013.08.003