Quaternary International 336 (2014) 44–51

Contents lists available at SciVerse ScienceDirect

Quaternary International

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

Statistical analysis of stream discharge in response to climate change for Urumqi River catchment, Tianshan Mountains, central Asia

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ARTICLE INFO

Article history:
Available online 10 May 2013

ABSTRACT

Understanding the impact of climate change on water resources is essential to sustainable development. Urumqi River, a medium-size headwater catchment in the Tianshan mountains, was chosen to evaluate the impact of climate change on its discharges, where impacts of human activities on water are negligible and the influence of glacier melt is minor as far as the mountainous outlet is concerned. Analysis of the time series of temperature, precipitation and river discharge of the hydrological station at the mountainous outlet from 1959 to 2006 was carried out using different statistical methods, including linear regression, Mann–Kendall test and wavelet analysis. Although both temperature and precipitation show a significant upward trend with a gradient of 0.02 °C/y and 2.08 mm/y, respectively, there is no significant rising trend in the stream discharge. The reasons are attributed to the hysteresis and buffering effects of groundwater in conveying the change from precipitation to stream discharge. Common short periods of less than 8 years exist in the three time series, which is a common trend in NW China. Precipitation has stronger influence on stream discharge than air temperature throughout the 48 years of instrumental records in the Urumqi River catchment.

1. Introduction

Climate warming during the last century has been recognized as a fact supported by both theoretical analysis and instrumental data (IPCC, 2007; Gregory et al., 2012). Changes in air temperature and precipitation have significant impacts on hydrological processes and water resources. Previous studies have mostly focused on the impact of climate change on river discharge to which glacier-melt water contributes a substantial part (Lafreniere and Sharp, 2003; Labat et al., 2004; Li et al., 2010) while few have done for non-glacier dominated catchments. Furthermore, human activities exacerbate the complexity of stream behavior through altering the natural recharge, flow and discharge. It is difficult to differentiate the individual impact of climate change from that of human factors on water resources (Jones, 2011; Tao et al., 2011). In order to avoid such ambiguity, an alternative method is to study river catchments in regions without human disturbance so as to focus on the single impact of climate change on water resources (Kong and Pang, 2011). Headwaters in alpine regions are one of the most appropriate research subjects for studies in this regard. This is because (1) alpine headwaters are almost free from the effects caused by human activities and (2) they are constituted of glacier-melt water, which is quite sensitive to temperature change. A wide variety of recent studies addressed this issue and examined the significance of climate change on water resources (Chen et al., 2006, 2008; Immerzeel et al., 2010; Li et al., 2011, 2010; Xu et al., 2011a,b).

Urumqi River, located in an alpine region in Northwest China, is a good example of this kind. Previous studies found that at Glacier No.1, which is the source of Urumqi River, discharge increased greatly due to the rise of temperature and precipitation from 1959 to 2006 (Li et al., 2007, 2010). Discharge of Urumqi River at Yingxiongqiao hydro-meteorological station, which is its mountainous outlet, is mainly composed of groundwater, with less than 9% glacier-melt water (Kong and Pang, 2012). Thus, the change of mountainous discharge and its response to climate change must be different from that at the source (Glacier No.1). The mechanism of Urumqi River's response to climate change could be comparable to other rivers that are not significantly affected by glacier-melt.

This paper examines the trend of change of climate and discharge of Urumqi River catchment and the interrelationship between them. Several statistical methods including linear regression, Mann–Kendall test, and wavelet analysis are used to

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http://dx.doi.org/10.1016/j.quaint.2013.05.002

delineate the changes, aiming at: 1) to detect any climate change effects in the time series of temperature, precipitation and discharge; 2) to identify possible co-variability of the three parameters; and 3) to assess impact of climate change on stream discharges at different time scales.

2. Study area

The Urumqi River catchment is located in Eastern Tianshan, Xinjiang Uygur Autonomous Region of China (Fig. 1). It is the main water source for the city of Urumqi. The shortage of water resources is one of the key restricting factors of the development of the city. For better water resources management in the future, it is vital to assess the impact of climate change on the Urumqi River and ascertain the mechanism of discharge change.

Xinjiang represents one sixth of China's land area. There are three major mountains that "border" the region, which are Altay Mts. in the north, Tianshan Mts. in the middle and Kunlun Mts. in the south. Between these mountains, there are two large basins, Junggar Basin and Tarim Basin.

There are five major air masses that influence the meteorological and pluviometric regime of Southeast Asia, and westerlies dominate Xinjiang (Pang et al., 2011; Kong et al., 2013). Xinjiang has a typical continental arid climate, where the annual average ambient temperature is 9–12 °C. In the mountainous region, precipitation is about 200–800 mm, and in the basin 10–200 mm. Throughout Xinjiang, the potential evaporation of open surface water bodies is 800–1200 mm in alpine regions and 1600–2200 mm in basins. Bare soil evaporation is 100–300 mm in the mountain regions, 250–400 mm in the agricultural development zone and 10–100 mm in deserts (Dong and Deng, 2005).

Urumqi River originates from Glacier No.1, flanking Tianger Peak II, the highest peak in the southeastern Tianshan Mountains with an elevation of 4484 m a.s.l. The total length of Urumqi River is 214.3 km with a drainage area of 4684 km^2, and the length in the mountainous area above the outlet (Yingxiongqiao station) is 62.6 km with a drainage area of 924 km^2 and an average altitude of 3483 m a.s.l. (Fig. 1).

3. Data and methods

3.1. Data

Two meteorological stations, Daxigou and Houxia, and five hydro-meteorological stations, Glacier No.1, Dry Circle, Total Control, Yuejinqiao, and Yingxiongqiao Stations are located along the main course of Urumqi River (see Fig. 1). The elevations of these stations range from 1900 m a.s.l. at Yingxiongqiao station to 3800 m a.s.l. at Dry circle station.

Stream flow and meteorological parameters were measured at the seven hydro-meteorological stations. Daily temperature and precipitation amount data at each meteorological station are monitored and internally published in annual reports of the Tianshan Glaciological Station (1980–2006), usually with a delay of a few years after data collection.

It is necessary to carry out data quality control before performing statistical analysis in order to eliminate the influence of erroneous outliers. The computer program RClimDex (available from http://cccma.seos.uvic.ca/ETCCDI/software.shtml), developed

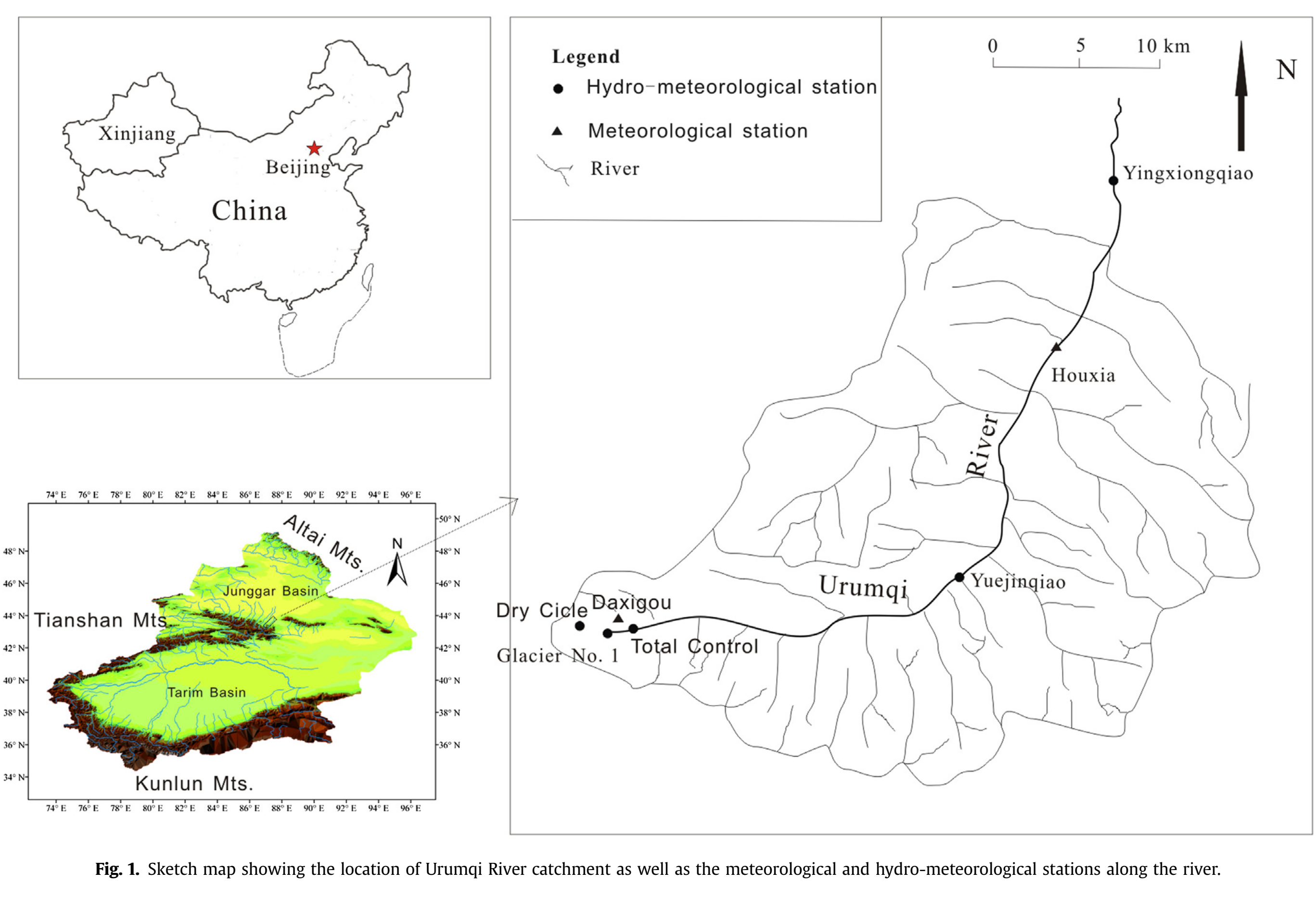

Fig. 1. Sketch map showing the location of Urumqi River catchment as well as the meteorological and hydro-meteorological stations along the river.

by Xuebin Zhang and Feng Yang at the Climate Research Branch of the Meteorological Service of Canada, has been found to be the best method for data quality control (Zhang et al., 2000, 2005; Li et al., 2011, 2012). The software identifies erroneous values and potential outliers of temperature and precipitation data, which were manually checked, validated, corrected, or removed. The potential outliers are defined as values outlying a user-defined threshold determined by the mean $\pm N$ standard deviations. In this paper, N is assigned to be 3 as the threshold for a striker quality control of the data. Homogeneity assessment and adjustment was also carried out with the Rhtest software (available from the ETCCDI Web site). Rhtest uses a two-phase regression model to check for multiple step change points that could exist in time series (Wang, 2003; Wang and Zhou, 2005). After data quality control and homogeneity assessment, the annual data were computed. They are consistent with the meteorological data in the Urumqi River catchment reported by previous studies (Li et al., 2003, 2007, 2010; Ye et al., 2005; Xu et al., 2011a). The observations at Yingxiongqiao hydrometeorological station have been carried out each year from 1958. The data can be obtained from He et al. (2009) and Kong and Pang (2012).

The data of temperature and precipitation at the seven stations stated and data of discharge at Yingxiongqiao station in the common time series from 1959 to 2006 are used. Different decomposition scale is highly relevant to the research objective (Labat et al., 2004): monthly fluctuations generally reflect the occurrence of low or high intensity events; annual fluctuations record the variations of the annual water budget highlighting dry and humid years; multi-annual fluctuations reflect the largest scale variations related to global general meteorological circulations and long term climate change. As the focus is on the impact of long-term climate change on discharge, the annual periods were analyzed, in order to minimize the inherent temporal noise of high resolution time series. Previous studies using the annual average of climatic and hydrological data show that the analysis at annual scale could reveal the interrelationship between climate and discharge change (Li et al., 2003, 2011, 2010).

3.2. Methods

It is important to choose an appropriate section of a river to assess the impact of climate change on discharge, because the river may have different variation patterns at different sections. Considering that the discharge at the mountainous outlet represents the total water resources in the catchments in arid regions, the Yingxiongqiao station, the mountainous outlet in Tianshan Mountains, was chosen. Li et al. (2010) stated that the observed temperature and precipitation at the three gauging stations of Glacier No.1, Dry Circle and Total Control have similar annual fluctuations to those at Daxigou meteorological station because of the close distance, which was confirmed by Xu et al. (2011a). Kong and Pang (submitted for publication) analyzed the annual trend at Glacier No.1 station and its relationship with glacier discharge. As this paper discusses the interrelationship between climate and discharge above the outlet of Eastern Tianshan Mountains, the weighted average of temperature and precipitation are calculated with watershed areas as weighting factor. The response of discharge to climate change in the sub-catchments will not be repeated here, but the comparisons of response at different sections will be presented in this paper.

Three statistical methods are used in this study to analyze the trend, period and interrelationship between temperature, precipitation and discharge in the Urumqi River catchment. A linear regression method, which is a parametric t-test method, is used to test the long-term linear trend. The Mann–Kendall test, which was originally devised by Mann (1945) as a non-parametric test for detecting trends and the distribution of the test statistic, derived by Kendall (1975), is used to test the non-linear trend, and further a revised sequential Mann–Kendall test by Goossens and Berger (1986) is used to detect the step change. Wavelet analysis is used to identify the periods of different time series and wavelet coherence is used to examine the interrelationship between them. Because the methods are in common usage (see Torrence and Compo, 1998; Torrence and Webster, 1999; Yue et al., 2002; Lafreniere and Sharp, 2003; Grinsted et al., 2004; Chen et al., 2007; Valdes-Galicia and Velasco, 2008; Chaouche et al., 2010; Ozger et al., 2010; Xu et al., 2011a,b; Wu et al., 2012; Zhai et al., 2013), descriptions of these methods are omitted here. The uncommon sequential Mann–Kendall test is summarized as follows.

Step change in the paper means a rather abrupt and permanent change during the period of hydrological/climatic record from one average value to another. However, it is difficult to identify the step change year when step change occurs due to the complicated dynamics and multiple factors affecting them (Fu and Wang, 1992). Goossens and Berger (1986) presented a graphical technique based on the Mann–Kendall method to detect the step change year. This graphical method has been verified by several studies with reasonable results (Jiang and You, 1996; Zhang et al., 2006; Yang and Tian, 2009). For a time series $X_1, X_2,\ldots X_N$, it uses the intersection of two curves: UFK and UBK. This method is based on the computation of all $\mathrm{U}(d_i)$,

$i = 1, 2\ldots N$:

$$\mathrm{U}(d_i) = (d_i - \mathrm{E}(d_i))/\sqrt{\mathrm{var}(d_i)} \quad (1)$$

in which d_i is given as:

$$d_i = m_1 + m_2 + \ldots + m_i \quad (2)$$

where, for each term X_i, the number m_i of terms X_j $(i > j)$ preceding it is calculated by

$$m_i = \begin{cases} 1 \text{ if } X_i - X_j > 0 \ \ \forall i > j \\ 0 \text{ if } X_i - X_j \le 0 \ \ \forall i > j \end{cases} \quad (3)$$

For the statistic d_i, its expected value is given as

$$\mathrm{E}(d) = N(N-1)/4 \quad (4)$$

and variance as

$$\mathrm{var}(d_i) = i(i-1)(2i+5)/72 \quad (5)$$

The graphical presentation of this ensemble of all $\mathrm{U}(d_i)$, $i = 1, 2\ldots N$, along the time series will be denoted as UFK. The sequential application to UFK of the rule issued for $\mathrm{U}(d)$ detects a change in the time series as soon as $\mathrm{U}(d_i)$ becomes larger than 1.96 (corresponding to $\alpha = 0.05$).

In order to localize the starting point of the change, the same principle is applied to the retrograde time series, the graphical representation of this ensemble will be denoted as UBK. In this case, for each term X_i, the number m'_i of terms X_j such that $X_i > X_j$ with $i < j$. Setting $i' = N + 1 - j$ and $m_{i'} = m'_i$, the values of $\mathrm{U}'(d_i)$ for the retrograde time series are given by

$$\mathrm{U}^{'}(d_i) = -\mathrm{U}(d_{i'}) \quad (6)$$

which gives $\mathrm{U}'(d_i) = -\mathrm{U}(d_N)$

The intersection of UFK and UBK localized the change, provided it is located between the critical of the 5% level of significance. This change here will be a step change, and the term *i* when the step change occurs is named step change year.

4. Results and discussion

4.1. Trend analysis

The statistics for temperature, precipitation and discharge time series are presented in Table 1, which reveal the range and shape of probability distribution of the three time series. A linear regression method, which is a parametric *t*-test method, is employed to test the long-term linear trend. Both temperature and precipitation show an increasing trend. However, there is not a significant rising trend in the record of discharge at Yingxiongqiao station. The findings obtained might only be used as a reference, because the hydrological and climatic time series are far from normal distribution. In the following text, non-parametric Mann–Kendall test without the requirement for normal distribution will be used to detect the trend and step-change year for comparison.

The time series of annual average temperature, precipitation and stream discharge are analyzed using the Mann–Kendall test. Both temperature and precipitation reveal a rising trend, with Z value $> Z_{1\text{-}\alpha/2}$ under the significance level of 5% (Table 2). Using Sen's non-parametric trend estimator (Sen, 1968) obtained the rising rate of temperature and precipitation with values of 0.02 °C/y and 2.08 mm/y, respectively. In accordance with the results of linear regression method, there is no significant increasing trend in the time series of discharge.

The sequential Mann–Kendall test was used to graphically illustrate the forward and backward trends of temperature, precipitation and discharge in the Urumqi River catchment from 1959 to 2006 (Fig. 2). The crossing point of upward and downward curves indicates the starting point of step change for temperature, precipitation and discharge during the period of 1959–2006. Step change in temperature and precipitation is significant ($P < 0.05$) at the point where the curves fall outside the dotted lines. The step change years for temperature and precipitation are identified as 1996 and 1988, respectively (see Table 2 and Fig. 2). The average temperature rises from 0.75 °C before 1996 to 1.72 °C after 1996. Annual precipitation increases from 327.89 mm to 390.47 mm with 1988 as the cut-off year. There is no significant step change in the time series of discharge.

It is interesting that discharge changes little while precipitation and temperature increase significantly. Several possible explanations may account for the phenomenon. Kong and Pang (2012) demonstrated the recharge sources to the Urumqi River at Yingxiongqiao station are groundwater, precipitation, and glacier-melt water. The discharge from Urumqi River includes discharge and evapotranspiration (Li, 2006). Pu et al. (2009) analyzed the annual trend of potential evapotranspiration in the Tianshan Mountains from 1971 to 2006 using Mann–Kendall method and found a slight decreasing rate of 0.448 mm/y. However, there are disputes on the relationship between potential evapotranspiration and actual evapotranspiration: a positive correlation (Peterson et al., 1995) or a negative one (Brutsaert and Parlange, 1998). Liu et al. (2008) calculated the evapotranspiration using the observation-constrained simulations with the NCAR Community Land Model and compared the variations of potential evapotranspiration and actual evapotranspiration from 1960 to 2005 in Xinjiang. Their results confirmed the decreasing of potential evapotranspiration but they also concluded that the actual evapotranspiration was increasing with a rate of about 0.2 mm/y in the past 50 years. The evapotranspiration could not explain the variations of discharge in the Urumqi River, because even the rising rate of 0.2 mm/y is far less than the increasing rate of 2.08 mm/y for precipitation. The recharge of glacier-melt water provides another possible reason. Nevertheless, Li et al., 2010 found that glacier-melt water increased greatly from 1959 to 2006. Obviously, the temporal change of discharge could not be attributed to the change of glacier-melt water. Precipitation and groundwater have caused the insignificant trend of discharge of Urumqi River at Yingxiongqiao station. In the following section, results of wavelet analysis will be used to further examine the relationship between temperature, precipitation and discharge.

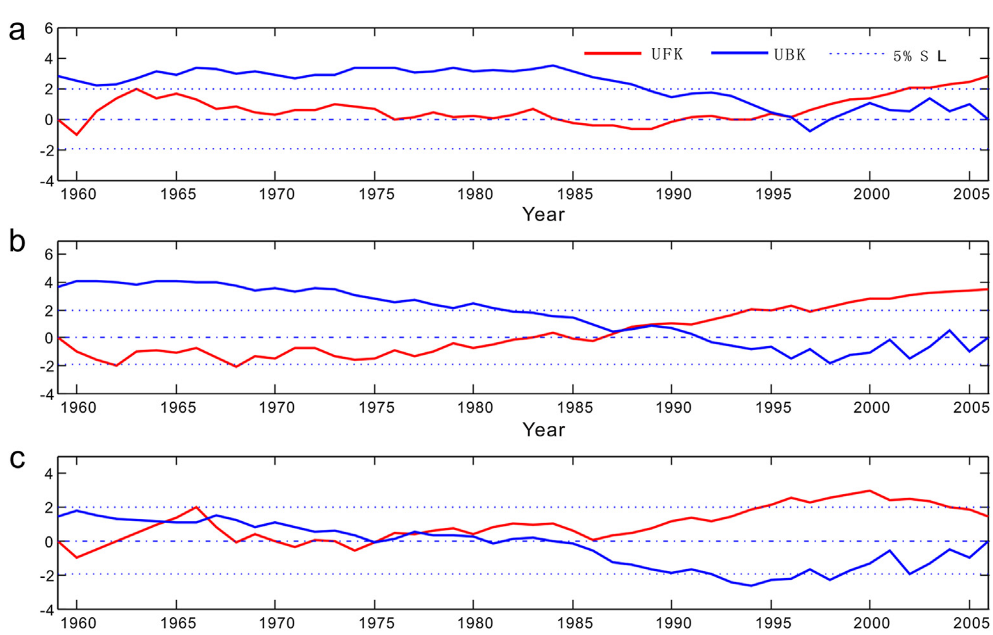

Fig. 2. Trend test and step change detection of temperature (a), precipitation (b) and discharge (c). Statistics UFK above 0 means a rising trend, otherwise a declining trend. Statistics UFK above or below 5% significance level illustrates a statistical significant trend. The crossing point of UFK and UBK is the year when step change occurs.

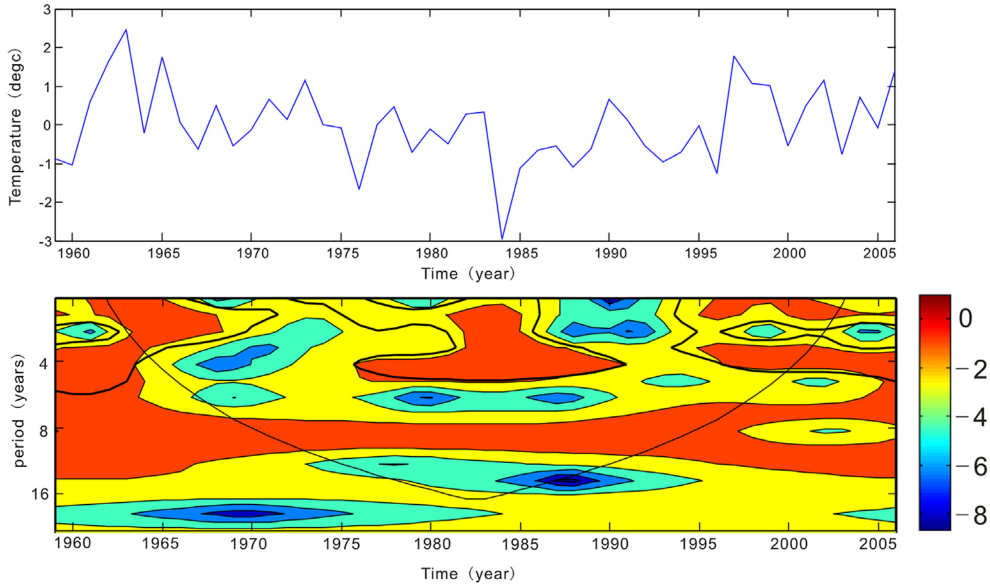

Fig. 3. Time series (above) and local wavelet power spectrum (below) of annual average temperature in the Urumqi River catchment. For the power spectrum figure: the left axis is the Fourier period (in *y*), and the bottom axis is time (*y*). The values of power spectrum can be seen according to the column on the right. The thick contour encloses regions of greater than 95% confidence for a red-noise process. The arc line is the 'cone of influence', below which edge effects become important.

4.2. Wavelet analysis

4.2.1. Periodic change

Figs. 3–5 reveal the periodic changes of temperature, precipitation and discharge in the Urumqi River catchment. The thick black contours designate significance level $\alpha = 0.05$ against red noise. Cross-hatched regions on either end indicate the cone of influence, where edge effects become important.

In the wavelet analysis of temperature, significantly high power was found during the computed periods before 1970, from 1975 to 1990 and after 1995, respectively, as well as a 2–6 y modulation of variation (Fig. 3). For precipitation, the power is broadly distributed, with peaks in 2–8 y (Fig. 4). The 5% significance regions indicate intervals of higher variance from 1970 to 1995 with a cycle of 2–8 y which changes to 2–6 y after 1995. The periodic change of precipitation is consistent with the regional climatic change in Eastern Tianshan, where step change occurs around the middle 1990s (Kong and Pang, submitted for publication).

The wavelet spectrum for discharge at Yingxiongqiao station shows that a 3–4 y cycle existed from 1965 to 1985, changing to a 3–6 y cycle after 1995 (Fig. 5). The periodic change is comparable to other rivers in Northwest China, such as periods of 10 and 17 y for tributaries of Tarim Rivers and a shorter period of 6–7 y for Heihe River (Wang and Meng, 2007; Chen et al., 2008).

4.2.2. Wavelet coherence

The squared wavelet coherence between temperature, precipitation and discharge is shown in Fig. 6, which reveals the localized

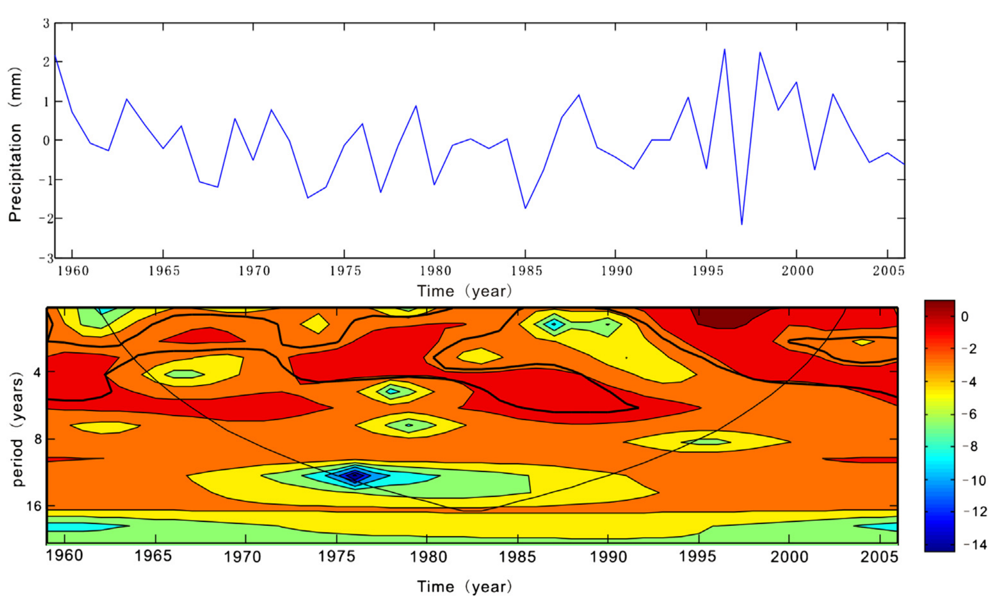

Fig. 4. Time series (above) and local wavelet power spectrum (below) of annual precipitation in the Urumqi River catchment. Legend as Fig. 3.

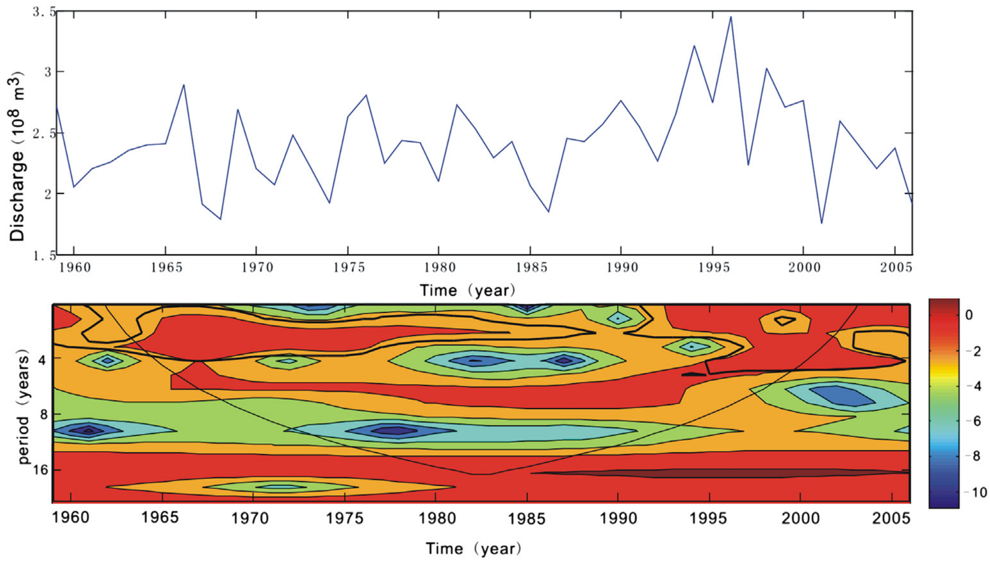

Fig. 5. Time series (above) and local wavelet power spectrum (below) of annual discharge at Yingxiongqiao station in the Urumqi River catchment. Legend as Fig. 3.

correlation in time frequency space. Directions of arrows and significance of the results show how the two time series are correlated. Arrows pointing straight right/left in phase denote linear positive/negative relationships, while arrows pointing up/down (out of phase) denote non-linear relationships (Grinsted et al., 2004).

Fig. 6a reveals that there is almost no coherence between temperature and discharge. Instead, precipitation and discharge share a cycle of 2–3 y during the years of 1964–1969, 1980–1984 and 1990–2006, and the periods become 2–4 y after 1995 (Fig. 6b). Most of the arrows in the regions with high coherence point to about 90 °C, revealing a significant linear correlation between them.

It is meaningful to compare the results for Yingxiongqiao station with those for Glacier No.1 station. It is clear that precipitation has a more profound effect on discharge than temperature at Yingxiongqiao station. Interestingly, this is contrary to the phenomena found in the discharge at Glacier No.1 station where temperature has a dominant effect (Kong and Pang, submitted for publication). The reason is that Urumqi River at Yingxiongqiao station is composed of less than 9% glacier melt water, while this fraction at Glacier No.1 station is more than 50% of the total discharge (Kong and Pang, 2012). A similar study by Xu et al. (2011b) also found the temperature has a dominant effect in Aksu River in Western Tianshan Mountains, where the fraction of glacier-melt water in the total discharge is higher than 50%. Temperature affects discharge by changing the component of glacier-melt water. Thus, rivers with more glacier-melt water are more sensitive to temperature change. This finding is consistent with the conclusion of isotopic studies that the nature of glacier rivers determines the climate sensitivity of watersheds fed by them (Kong and Pang, 2012).

Urumqi River is mainly composed of groundwater, which comes from the infiltration of precipitation and glacier-melt water. Therefore, stream discharge can be affected through groundwater input and/or direct precipitation. Change in phase between

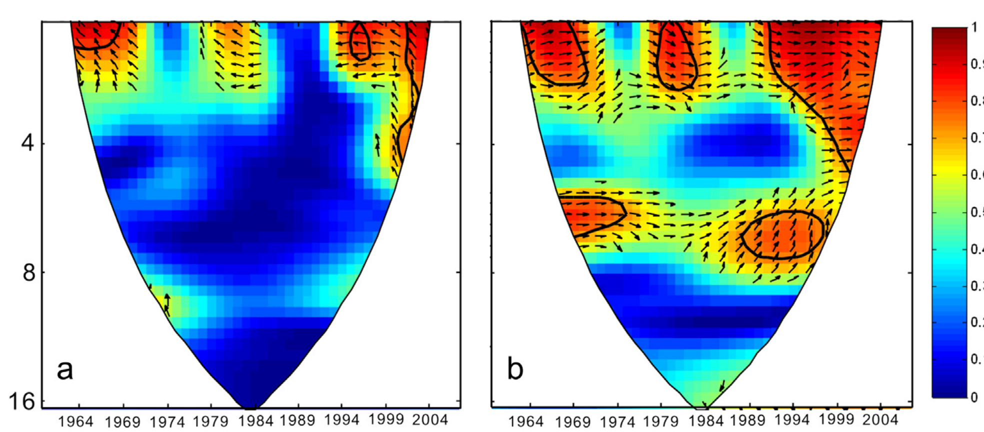

Fig. 6. Squared wavelet coherence between discharge and temperature (a) and precipitation (b) in the Urumqi River catchment. The values can be seen according to the colorful column on the right. The thick black contour designated the 5% significance level against red noise. The cone of influence (COI) where edge effects might distort the picture is shown as a light shade. The *X* axis corresponds to the physical time and *Y* axis corresponds to scales in years. The vectors indicate the phase difference (a horizontal arrow pointing from left to right signifies in-phase and an arrow pointing vertically upward means the second series lags the first by 90°).

precipitation and discharge shows that precipitation has a dominant effect on Urumqi River relative to temperature. The analysis above highlights the importance of precipitation on discharge of Urumqi River. This provides a basis to assess the response of stream discharge to climate change in Northwest China. It has implications for water resources management under the stress of climate change and human activities in the lower reach of Urumqi River, where groundwater level has declined remarkably (Zhu et al., 2007).

The study shows that discharge of Urumqi River at Yingxiongqiao station has basically remained unchanged during the past 48 y, although the temperature and precipitation have increased significantly. This could be attributed to the hysteresis and buffering effect of groundwater because the evapotranspiration and glacier-melt water can be excluded. There are thick deposits of sandstone and conglomerate in Tianshan Mountains, due to the uplift driven by the India–Asia collision (Charreau et al., 2005), which provide a suitable natural hydrogeological condition for infiltration of precipitation and for the storage of groundwater. Wang (2007) found that the shallow groundwaters in the Urumqi River catchment are generally young, characterized with average tritium of 37 TU in the mountainous regions, implying that groundwater can be easily recharged by precipitation. When the aquifers are cut by rivers in the Urumqi River catchment, groundwater tends to recharge the river (Li, 2006). From the source of Glacier No.1 to the outlet at Yingxiongqiao station, the ratio of recharging groundwater to Urumqi River increases gradually (Li, 2006; Kong and Pang, 2012). The lower rate of groundwater recharging surface water in the mountainous regions reduces the sensitivity of discharge to climate change.

5. Conclusions

In this study, temporal trends of temperature, precipitation and stream discharge as well as their interrelationship were examined. The following conclusions are drawn:

(1) There are significant rising trends of temperature and precipitation in the Urumqi River catchment, but the discharge of Urumqi River does not show significant rising trend over the past 48 years. The reasons are attributed to the hysteresis and buffering effect of groundwater, which is the main component of Urumqi River discharge.
(2) The step change years of temperature and precipitation records are identified and significant high power of variance exists in the time series of temperature, precipitation and discharge in the Urumqi River catchment, with a modulation of variance less than 8 y.
(3) Precipitation is found to have a primary effect on the discharge compared to temperature throughout the instrumental records.

Table 2
Results of Mann–Kendall trend test for temperature, precipitation and discharge of Urumqi River at Yingxiongqiao station.

Item	Time series	*Z*	*K* (/y)	Step change year	H0
Temperature (°C)	1959–2006	2.78	0.02	1996	R
Precipitation (mm)	1959–2006	3.56	2.08	1988	R
Discharge (10^8 m^3)	1959–2006	1.44	\	\	A

Notes: R: Rejected; A: Accept; Significance level = 5%; *Z* is statistics of Mann–Kendall test; *K* is gradient; y: year.

Acknowledgments

This study is supported by the Innovation Program of Chinese Academy of Sciences (Grant kzcx2-yw-127) and the National Natural Science Foundation of China (Grants 40672171 and 40872162). Sincere appreciation is given to Dr. Christopher Torrence and Dr. Gilbert P. Compo for providing the wavelet software and to Dr. Aslak Grinsted for providing the wavelet coherence software. The thoughtful and constructive comments of three anonymous reviewers and guest editor Lu Xixi (National University of Singapore) are gratefully acknowledged.

References

Brutsaert, W., Parlange, M.B., 1998. Hydrologic cycle explains the evaporation paradox. Nature 396, 30.
Chaouche, K., Neppel, L., Dieulin, C., Pujol, N., Ladouche, B., Martin, E., Salas, D., Caballero, Y., 2010. Analyses of precipitation, temperature and evapotranspiration in a French Mediterranean region in the context of climate change. Comptes Rendus Geoscience 342, 234–243. http://dx.doi.org/10.1016/j.crte.2010.02.001.
Charreau, J., Chen, Y., Gilder, S., Dominguez, S., Avouac, J.P., Sen, S., Sun, D., Li, Y., Wang, W., 2005. Magnetostratigraphy and rock magnetism of the Neogene Kuitun He section (northwest China): implications for Late Cenozoic uplift of the Tianshan mountains. Earth and Planetary Science Letters 230, 177–192.
Chen, Y., Takeuchi, K., Xu, C., Chen, Y., Xu, Z., 2006. Regional climate change and its effects on river discharge in the Tarim Basin China. Hydrological Processes 20, 2207–2216.
Chen, H., Guo, S., Xu, C., Singh, V., 2007. Historical temporal trends of hydro-climatic variables and runoff response to climate variability and their relevance in water resource management in the Hanjiang basin. Journal of Hydrology 344, 171–184.
Chen, Y., Pang, Z., Hao, X., Xu, C., Chen, Y., 2008. Periodic changes of stream flow in the last 40 years in Tarim River Basin, Xinjiang, China. Hydrological Processes 16, 1371–1379.
Dong, X., Deng, M., 2005. Xinjiang Groundwater Resources. Xinjiang Science and Technology Press, Urumqi, China, p. 193.
Fu, C., Wang, Q., 1992. The definition and detection of the abrupt climatic change. Scientia Atmospherica Sinica 16, 482–493.
Goossens, C., Berger, A., 1986. Annual and seasonal climatic variations over the northern hemisphere and Europe during the last century. Annals in Geophysics 4, 385–400.
Gregory, J., White, N., Church, J., Bierkens, M., Box, J., van den Broeke, v., Cogley, J., Fettweis, X., Hanna, E., Huybrechts, P., Konikow, L., Leclercq, P., Marzeion, B., Oerlemans, J., Tamisiea, M., Wada, Y., Wake, M., van de Wal, R., 2012. Twentieth-century global-mean sea-level rise: is the whole greater than the sum of the parts? Journal of Climate. http://dx.doi.org/10.1175/JCLI-D-12-00319.1.

Table 1
Statistics for temperature, precipitation and discharge time series of Urumqi River at Yingxiongqiao station. From Column 2 to Column 8, the statistics are values of multi-year mean, maximum, minimum, variance, standard deviation, variation coefficient, skewness coefficient and Kurtosis coefficient of temperature, precipitation and discharge from 1959 to 2006.

	Mean	Max.	Min.	Variance	Standard dev.	Variation coeff.	Skewness coeff.	Kurtosis coeff.
Temperature (°C)	0.95	2.33	−0.81	0.44	0.67	0.03	0.18	0.70
Precipitation (mm)	351.36	499.85	254.85	3558.31	59.65	0.55	0.22	0.17
Discharge (10^8 m^3)	2.42	3.45	1.75	0.13	0.36	0.42	0.49	0.15

Grinsted, A., Moore, J., Jevrejeva, S., 2004. Application of the cross wavelet transform and wavelet coherence to geophysical time series. Nonlinear Processes in Geophysics 11 (5/6), 561–566.
He, L., Gong, J., Zhao, Y., 2009. Trend analysis on change of runoff and sediment in Urumqi River. Science and Technology in Western China 8, 1–3.
Immerzeel, W., van Beek, L., Bierkens, M., 2010. Climate change will affect the Asian water towers. Science 328. http://dx.doi.org/10.1126/science.1183188.
IPCC, 2007. Climate Change 2007: the Physical Science Basis. Report of Working Group I of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.
Jiang, J.M., You, X.T., 1996. Where and when did an abrupt climate change occur in China during the last 43 years? Theoretical and Applied Climatology 55, 33–39.
Jones, J., 2011. Hydrologic responses to climate change: considering geographic context and alternative hypotheses. Hydrological Processes 25, 1996–2000.
Kendall, M., 1975. Rank Correlation Methods. Griffin, London.
Kong, Y., Pang, Z. Runoff changes and controlling factors at a small glacial watershed in Tianshan Mountains, Central Asia. Hydrological Sciences Journal. (Submitted for publication).
Kong, Y., Pang, Z., Froehlich, K., 2013. Quantifying recycled moisture fraction in precipitation of an arid region using deuterium excess. Tellus 65B. http://dx.doi.org/10.3402/tellusb.v65i0.19251.
Kong, Y., Pang, Z., 2011. Isotope hydrograph separation in alpine catchments: a review. Science of Cold and Arid Regions 3 (1), 86–91.
Kong, Y., Pang, Z., 2012. Evaluating the sensitivity of glacier rivers to climate change based on hydrograph separation of discharge. Journal of Hydrology 434–435, 121–129. http://dx.doi.org/10.1016/j.jhydrol.2012.02.029.
Labat, D., Godderis, Y., Probst, J., Guyot, J., 2004. Evidence for global runoff increase related to climate warming. Advances in Water Resources 27, 631–642.
Lafreniere, M., Sharp, M., 2003. Wavelet analysis of inter annual variability in the runoff regimes of glacial and nival stream catchments, Bow Lake, Alberta. Hydrological Processes 17, 1093–1118.
Li, Z., Shen, Y., Wang, F., Li, H., Dong, Z., Wang, W., Wang, L., 2007. Response of glacier melting to climate change. Journal of Glaciology and Geocryology 29, 333–342.
Li, Z., Wang, W., Zhang, M., Wang, F., Li, H., 2010. Observed changes in streamflow at the headwaters of the Urumqi River, eastern Tianshan, central Asia. Hydrological Processes 24, 217–224.
Li, J.F., 2006. Climatic data. In: Li, J.F. (Ed.), Hydrology and Climate Datasets for the Wulumuqi River Catchments (in Chinese). China Meteorological Press, Beijing, China, pp. 75–130.
Li, Z., Han, T., Jin, Z., Yang, H., Jiao, H., 2003. A summary of 40-year observation facts of climate and Glacier No.1 at headwater of Urumqi River, Tianshan, China. Journal of Glaciology and Geocryology 25, 117–123.
Li, Z., He, Y., Wang, C., Wang, X., Xin, H., Zhang, W., Cao, W., 2011. Spatial and temporal trends of temperature and precipitation during 1960–2008 at the Hengduan Mountains, China. Quaternary International 236, 127–142.
Li, Z.X., He, Y.Q., An, W.L., Song, L.L., Zhang, W., Norm, C., Wang, Y., Wang, S.J., Liu, H.C., Cao, W.H., Theakstone, W.H., Wang, S.X., Du, J.K., 2011. Climate and glacier change in southwestern China during the past several decades. Environmental Research Letters 6. http://dx.doi.org/10.1088/1748-9326/6/4/045404.
Li, Z.X., He, Y.Q., Wang, P.Y., Theakstone, W.H., An, W.L., Wang, X.F., Lu, A.G., Zhang, W., Cao, W.H., 2012. Changes of daily climate extremes in southwestern China during 1961–2008. Global and Planetary Change 80-8, 255–272.
Liu, B., Ma, Z., Feng, J., Wei, R., 2008. The relationship between pan evaporation and actual evapotranspiration in Xinjiang since 1960. Acta Geographica Sinica 63, 1131–1139.
Mann, H., 1945. Nonparametric tests against trend. Econometrica 13, 245–259.
Ozger, M., Mishra, A., Singh, V., 2010. Scaling characteristics of precipitation data inconjunction with wavelet analysis. Journal of Hydrology 395, 279–288.
Pang, Z., Kong, Y., Froehlich, K., Huang, T., Yuan, L., Li, Z., Wang, F., 2011. Processes affecting isotopes in precipitation of an arid region. Tellus 63B, 352–359.
Peterson, T.C., Golubev, V.S., Groisman, P.Y., 1995. Evaporation losing its strength. Nature 377, 687–688.
Pu, Z., Zhang, S., Wang, S., Li, J., Liu, M., Sun, Y., 2009. Study on the change of annual potential evapotranspiration in the Tianshan Mountains in recent 36 years and its comparison with that in South Xinjiang and North Xinjiang. Arid Zone Research 26, 424–432.
Sen, P., 1968. Estimates of the regression coefficient based on Kendall's tau. Journal of the American Statistical Association 63, 1379–1389.
Tao, H., Gemmer, M., Bai, Y., Su, B., Mao, W., 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.
Tianshan Glaciological Station, 1980–2006. Annual Report of Tianshan Glaciological Station, vol. 1–18. Tianshan Glaciological Station Press, Lanzhou.
Torrence, C., Compo, G., 1998. A practical guide to wavelet analysis. Bulletin of the American Meteorological Society 79, 61–78.
Torrence, C., Webster, P., 1999. Interdecadal changes in the ESNO monsoon system. Journal of Climate 12, 2679–2690.
Valdes-Galicia, J., Velasco, M., 2008. Variations of mid-term periodicities in solar activity physical phenomena. Advances in Space Research 41, 297–305.
Wang, J., 2007. Study on Water Environmental Isotopes in Northern Piedmont of Tianshan Mountains. dissertation. Changan University, pp. 1–87.
Wang, J., Meng, J., 2007. Research on runoff variations based on wavelet analysis and wavelet neural network model: a case study of the Heihe River drainage basin (1944–2005). Journal of Geographical Sciences 17 (3), 327–338.
Wang, X.L., 2003. Comments on "detection of undocumented change points: a revision of the two-phase regression model". Journal of Climate 16, 3383–3385.
Wang, Y.Q., Zhou, L., 2005. Observed trends in extreme precipitation events in China during 1961–2001 and the associated changes in large-scale circulation. Geophysical Research Letters 32, L09707. http://dx.doi.org/10.1029/2005GL022574.
Wu, C., Yang, S., Lei, Y., 2012. Quantifying the anthropogenic and climatic impacts on water discharge and sediment load in the Pearl River (Zhujiang), China (1954–2009). Journal of Hydrology. http://dx.doi.org/10.1016/j.jhydrol.2012.05.064.
Xu, J., Chen, Y., Lu, F., Li, W., Zhang, L., Hong, Y., 2011b. The nonlinear trend of runoff and its response to climate change in the Aksu River, western China. International Journal of Climatology 31, 687–695.
Xu, X., Pan, B., Hu, E., Li, Y., Liang, Y., 2011a. Responses of two branches of glacier No. 1 to climate change from 1993–2005, Tianshan, China. Quaternary International 236, 143–150.
Yang, Y., Tian, F., 2009. Abrupt change of runoff and its major driving factors in Haihe River catchment, China. Journal of Hydrology 374, 373–383.
Ye, B., Yang, D., Jiao, K., Han, T., Jin, Z., Yang, H., Li, Z., 2005. The Urumqi River source glacier No. 1, Tianshan, China: changes over the past 45 years. Geophysical Research Letters 32, L21504. http://dx.doi.org/10.1029/2005GL024178.
Yue, S., Pilon, P., Cavadias, G., 2002. Power of the Mann-Kendall and Spearman's rho tests for detecting monotonic trends in hydrologic series. Journal of Hydrology 259, 254–271.
Zhai, Y., Guo, Y., Zhou, J., Guo, N., Wang, J., Teng, Y., 2013. The spatio-temporal variability of annual precipitation and its local impact factors during 1724–2010 in Beijing, China. Hydrological Processes. http://dx.doi.org/10.1002/hyp.9772.
Zhang, Q., Liu, C., Xu, C.Y., Xu, Y.P., Jiang, T., 2006. Observed trends of annual maximum water level and streamflow during past 130 years in the Yangtze River basin, China. Journal of Hydrology 324 (1–4), 255–265.
Zhang, X.B., et al., 2005. Trends in Middle East climate extreme indices from 1950 to 2003. Journal of Geophysical Research 110, D22104. http://dx.doi.org/10.1029/2005JD006181.
Zhang, X.B., Vincent, L.A., Hogg, W.D., Niitsoo, A., 2000. Temperature and precipitation trends in Canada during the 20th century. Atmosphere and Ocean 38, 395–429.
Zhu, J., Huo, C., Jiang, Y., Gong, X., Li, H., Wang, J., Li, W., Zhou, Y., 2007. Monitoring of regional groundwater level in Urumqi River Basin. Hydrogeology and Engineering Geology 2, 8–14.