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ORIGINAL PAPER

An integrated statistical approach to identify the nonlinear trend of runoff in the Hotan River and its relation with climatic factors

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Abstract A number of studies have indicated a transition from warm-dry to warm-wet climate in Northwest China after the 1980s. This transition was characterized by an increase in temperature and precipitation, added river runoff volume, increased lake water surface elevation and area, and elevated groundwater table. However, some literatures showed that the Hotan River has presented a contrary situation, i.e. the runoff decreased, whereas temperature and precipitation increased. In order to discover the nonlinear runoff trend and its causes in the Hotan River, based on the related data from hydrological stations, ground and air sounding meteorological stations, this study applied a comprehensive method combing correlation analysis, wavelet analysis and regression analysis to investigate the runoff change in the Hotan River with its relevant climatic factors over the past decades. The main findings are: (a) the hydrological process of the Hotan River is a nonlinear system, with a periodicity of 24 year cycle, and it shows different nonlinear trends at different time scales; (b) the data from the ground meteorological stations in the Hotan area shows a false appearance that there is almost no correlation between runoff and temperature, and a little negative correlation between runoff and precipitation; (c) but the data from air sounding meteorological stations shows the truth that there is a close relation between the runoff in the Hotan River and the 0°C level height in summer on the north slope of Kunlun Mountains. The two variables present a same periodicity, i.e. 24-year cycle, having similar nonlinear trends and significant correlations at different time scales.

Keywords Runoff · Climatic factor · Nonlinear trend · Correlation · Wavelet approximation · Wavelet regression analysis · The Hotan River · Northwest China

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1 Introduction

In the last decade many studies have been conducted to evaluate climate change and the hydrological processes in the arid regions of Northwest China. When the evidence of global runoff increase related to climate warming was highlighted (Labat et al. 2004), a number of studies (Zhang et al. 2003; Chen and Xu 2005; Chen et al. 2006; Wang et al. 2006; Shi et al. 2007) showed that there was a salient turning point in the hydrological and climatic processes in the arid regions of Northwest China after the 1980s. This new trend was characterized by a continual increase in temperature and precipitation, added river runoff volume, increased lake water surface elevation and area, and elevated groundwater level. These changes have led to increased water resources, providing immediate relief to the local water shortage. Especially in the Tarim River basin, both increasing precipitation and accelerating melting ice have increased streamflow (Zhang et al. 2009). However, some studies showed that, as one of headwaters of the Tarim River, the Hotan River has presented a contrary situation, i.e. the runoff has been decreasing continuously (Shen et al. 2003; Zhang et al. 2007), while temperature and precipitation increasing (Yusup et al.

2006). Is it really an exception for the Hotan River? What are the reasons for this? To date, the previous studies have not yet thoroughly answer these questions.

In fact, the hydro-climatic processes with nonlinear mechanism in the arid region of Northwest China are very complicated systems (Xu et al. 2010a, b), and relations between streamflow and climate factors are not understood thoroughly (Xu et al. 2008a, 2009a). It is difficult to model the physical hydro-climatic process because of the difficulties to obtain extensive precise data on underlying surface by the grid method, whereas traditional statistical analysis cannot directly deal with the complicated nonlinear process of the hydro-climatic system (Xu et al. 2008b, 2009b). To date, these questions have not been answered satisfactorily; therefore, more studies are required to explore the nonlinear characteristics of hydro-climatic processes from different perspectives using different methods.

In order to discover the change trend of runoff and its causes in the Hotan River during the past few decades, based on the related data from hydrological stations, ground and air sounding meteorological stations, this study applied an integrated statistical method combing correlation analysis, wavelet analysis and regression analysis to investigate the nonlinear trend of runoff in the Hotan River and its relevant climatic factors over the past decades.

2 Materials and methods

2.1 Study area

Originating from the north slope of Kunlun Mountains, with two tributaries, the Karakash and Yulongkash River, the Hotan River is situated in the Tarim River Basin, which is enclosed between latitudes 34°28′–40°28′ N and longitudes 77°25′–81°43′ E (Fig. 1) covering an area of 48,870 km^2. As an inland river basin, showing a clear vertical zones from south (high terrain) to north (low terrain), the Hotan River basin can be divided into four vertical landscape zones, that is, the upper reaches of glacier, snow and tundra in the high Kunlun Mountains, vegetation belt of the north Slope in the middle Kunlun Mountains, the middle plain areas of the oasis, and the lower reaches of the desert belt. In the high Kunlun Mountains, there are 3,555 glaciers with an area of 5336.98 km^2 and ice volume of 578.71 km^3, and the snow line altitude between 4,780 and 6,260 m. The stream flow of Hotan River is mainly from glaciers and snow melt, and highly concentrated in summer (Wu et al. 2006). For the two tributaries, the Yulongkash River and Karakash River, the ratio of runoff in summer is as high as 80.7% and 72.9% (Shi 2005). There are full of mountain steppe and alpine meadow in the vegetation belt of the north slope in the middle Kunlun Mountains. In the middle plain areas of the oasis and the lower reaches of the desert belt, it has a temperate continental arid climate with the characteristics such as drought, lack of rainfall, intensity evaporation, and large temperature difference between days and years. Furthermore, the multi-year average temperature, precipitation, evaporation in the drainage, are 12.2°C, 36.9 mm and 2545.5 mm, respectively; annual extreme maximum and minimum temperature are 43.7 and −28.9°C; and the multi-year mean sunshine duration is 3,000 h.

2.2 Data

To evaluate the nonlinear trend in annual runoff in the Hotan River, the annual data from 1959 to 2005 for the two sub-rivers were used. The data were obtained from the Wuluwat and Tonguzluok hydrological stations, their locations were marked in Fig. 1. The elevation of the two hydrological stations is 1,800 m at Wuluwat, and 1,650 m at Tonguzluok, respectively.

Because the two stations are close to the source areas of the rivers, the amount of water used by humans within each tributary basin is minimal compared to the total discharge; therefore, it was assumed that the observed hydrological records reflect the natural conditions.

To investigate the relationship between the runoff and the regional climatic factors, this study used the annual average temperature and annual precipitation data from 7 ground meteorological stations in the Hotan area (i.e. Kash, Pishan, Hotan, Minfeng, Yutian, Qiemo, and Ruoqiang station), and the data of 0°C level height in summer from 4 air sounding meteorological stations on the north slope of the Kunlun Mountains (i.e. Kash, Hotan, Qiemo, and Ruoqiang station) for the same study period. The location and elevation of each ground and air sounding meteorological station are marked in Fig. 1 and Table 1, respectively.

The observation methods of each ground and air sounding meteorological station are conventional methods. The observation period of air sounding meteorological stations is summer each year, including June, July and August. The data of the 0°C level height in summer used in this paper is the mean of monthly data in summer, each monthly data is the mean of daily data, and the daily data is the mean of the two observed data in a day, which is obtained on 8:00 and 20:00 o'clock, respectively.

2.3 Methodology

During the past decade, there has been considerable effort devoted to obtaining a better understanding for natural climate fluctuations to impact water resources (Terray and Cassou 2000; Chen and Xu 2005; Kim et al. 2007; Kim et al. 2008). However, the mechanisms governing the

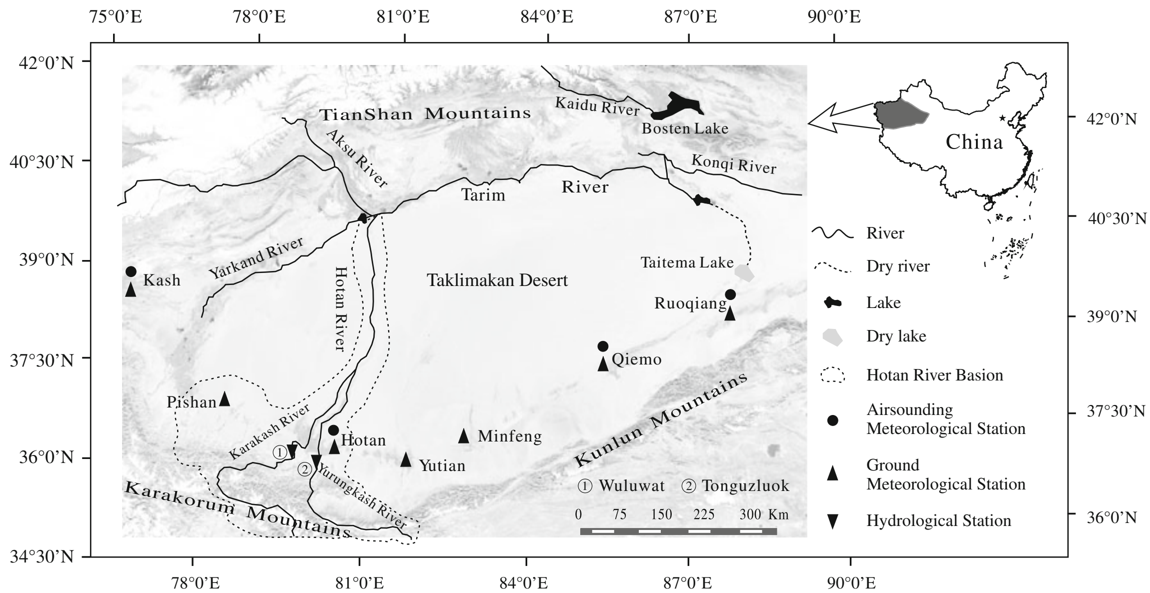

Fig. 1 Location of the Hotan River

Table 1 The location and elevation of ground and air sounding meteorological stations in the Hotan area

Station	Type	Longitude	Latitude	Elevation (m)
Kash	Ground, air sounding	E 75°59′	N 39°28′	1293.6
Pishan	Ground	E 78°17′	N 37°37′	1376.4
Hotan	Ground, air sounding	E 79°56′	N 37°08′	1374.9
Minfeng	Ground	E 82°43′	N 37°04′	1410.6
Yutian	Ground	E 81°39′	N 36°51′	1423.3
Qiemo	Ground, air sounding	E 85°33′	N 38°09′	1248.4
Ruoqiang	Ground, air sounding	E 88°10′	N 39°02′	888.4

relationship between the climatic variability and streamflow are still not fully understood (Xu et al. 2010b). In order to identify and understand the different aspects of runoff's nonlinear trend and its relevant climatic factors, combing correlation analysis, wavelet analysis and regression analysis, this paper brought an integrated method named wavelet regression analysis. Firstly, correlation analysis was used to check the correlations between the runoff of the Hotan River and the regional climate factors, such as temperature and precipitation. Secondly, wavelet analyses were used to reveal the periodicity and nonlinear trend of runoff and its related climatic factors. Thirdly, based on the results of wavelet analysis, the quantitative relation between the runoff and the 0°C level height in summer on the north slope of the Kunlun Mountains was revealed by using the regression analysis method.

2.3.1 Correlation analysis

The correlation is one of the most common and most useful statistical methods, which is a statistical measurement of the relationship between two variables (Zimmerman 1986). Possible correlations range from +1 to −1. A zero correlation indicates that there is no relationship between the variables. A negative correlation indicates that as one variable goes up, the other goes down. A positive correlation indicates that both variables move in the same direction together.

For the two variables, x and y, the correlation coefficient is calculated as:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i-\bar{y})^2}} \quad (1)$$

where, n is the sample number; x_i represent the value of x for the sample i; y_i represent the value of y for the sample i; $\bar{x}$ is the mean for all x_i; $\bar{y}$ is the mean for all y_i. Test for the significance of the correlation coefficient commonly employs the t distribution (Zimmerman 1986).

The correlation analysis was used to check the correlations between the runoff of the Hotan River and the regional climate factors, such as temperature and precipitation in this study.

2.3.2 Wavelet analysis

Wavelet transformation has been shown to be a powerful technique for characterization of the frequency, intensity, time position, and duration of variations in climate and hydrological time series (Smith et al. 1998; Labat et al. 2004; Chou 2007; Xu et al. 2008a, b; Partal 2009). Wavelet analysis can also reveal the localized time and frequency information without requiring the time series to be stationary, as required by the Fourier transform and other spectral methods (Torrence and Compo 1998).

A continuous wavelet function $\Psi(\eta)$ that depends on a non-dimensional time parameter η can be written as (Labat 2005):

$$\Psi(\eta) = \Psi(a,b) = |a|^{-1/2}\Psi\left(\frac{t-b}{a}\right) \tag{2}$$

where, t denotes time, a is the scale parameter and b is the translation parameter. $\Psi(\eta)$ must have a zero mean and be localized in both time and Fourier space (Farge 1992). The continuous wavelet transform (CWT) of a discrete signal, $x(t)$, such as the time series of runoff, temperature, or precipitation, is expressed by the convolution of $x(t)$ with a scaled and translated $\Psi(\eta)$,

$$W_x(a,b) = |a|^{-1/2}\int_{-\infty}^{+\infty} x(t)\Psi^*\left(\frac{t-b}{a}\right)\mathrm{d}t \tag{3}$$

where, * indicates the complex conjugate, and $W_x(a, b)$ denotes the wavelet coefficient. Thus, the concept of frequency is replaced by that of scale, which can characterize the variation in the signal, $x(t)$, at a given time scale.

The wavelet variance that is used to detect the periods present in the signal, $x(t)$, can be expressed as:

$$W_x(a) = \int_{-\infty}^{+\infty} |W_x(a,b)|^2\mathrm{d}b \tag{4}$$

Selecting a proper wavelet function is a prerequisite for time series analysis. The actual criteria for wavelet selection include self-similarity, compactness, and smoothness (Ramsey 1999). For the present study, symlet 8 was chosen as the base wavelet according to these criteria.

The nonlinear trend of a time series, $x(t)$, can be analyzed at multiple scales through wavelet decomposition on the basis of the discrete wavelet transform (DWT). The DWT is defined taking discrete values of a and b. The full DWT for signal, $x(t)$, can be represented as (Mallat 1989):

$$x(t) = \sum_k \mu_{j_0,k}\phi_{j_0,k}(t) + \sum_{j=1}^{j_0}\sum_k \omega_{j,k}\psi_{j,k}(t) \tag{5}$$

where $\phi_{j_0,k}(t)$ and $\psi_{j,k}(t)$ are the flexing and parallel shift of the basic scaling function, $\phi(t)$, and the mother wavelet function, $\psi(t)$, and $\mu_{j_0,k}(j<j_0)$ and $\omega_{j,k}$ are the scaling coefficients and the wavelet coefficients, respectively. Generally, scales and positions are based on powers of 2, which is the dyadic DWT.

Once a mother wavelet is selected, the wavelet transform can be used to decompose a signal according to scale, allowing separation of the fine-scale behavior (detail) from the large-scale behavior (approximation) of the signal (Bruce et al. 2002). The relationship between scale and signal behavior is designated as follows: low scale corresponds to compressed wavelet as well as rapidly changing details, namely high frequency; whereas high scale corresponds to stretched wavelet and slowly changing coarse features, namely low frequency. Signal decomposition is typically conducted in an iterative fashion using a series of scales such as $a = 2, 4, 8, \ldots, 2^L$, with successive approximations being split in turn so that one signal is broken down into many lower resolution components.

2.3.3 Wavelet regression analysis

The hydro-climatic process of Hotan River is a nonlinear system because of the complex geographical and environmental background, and maybe it is difficult to establish the statistical relationship between runoff and climatic factors as it was commonly done in many other researches (Xu 2002; Lee and Chung 2007; Chen et al. 2009). To understand the change trend of runoff and its causes during the past decades, this paper also employed a wavelet regression analysis to examine the nonlinear trend of runoff in the Hotan River and its climatic effect factors. The analysis steps are as follows (Xu et al. 2008b): (1) firstly, nonlinear trends of runoff and its relevant climate factors, such as annual runoff and the average height of 0°C level in summer were approximated by using wavelet decomposition on the basis of the discrete wavelet transform (DWT) at different time scales; (2) then, the statistical relationship between annual runoff and the average height of 0°C level in summer were revealed by using regression analysis method based on the results from wavelet approximation.

3 Results and discussion

Many studies focused on the climatic transition from warm-dry to warm-wet in Northwest China in the past 10 years, but the most were based on the data from ground meteorological stations. Lacking of the meteorological data in the high mountains and that from the ground meteorological stations are interfered by noises, people have not quantitatively understand the causes for the change of the river runoff from the glacier and snowmelt in high mountains (Zhang 2007). In order to thoroughly investigate the runoff of Hotan River and its related climatic factors, we should use the data as possible as we can to collect from the ground and air sounding meteorological stations.

3.1 Nonlinear trend of runoff

The time series of annual runoff in the Hotan River is showed in Fig. 2, which appeared fluctuating patterns for the period of 1959–2005 (Fig. 2). Apparently, it is difficult to identify any trends (e.g. periodicity) simply based on the surface of the oscillation pattern. This issue was addressed here using wavelet analysis.

3.1.1 Periodicity of runoff

Based on the wavelet function of symlet 8, which was selected according to the criteria of self-similarity, compactness and smoothness (Ramsey 1999), the CWT was applied to the annual runoff time series. The computed wavelet variances (Fig. 3) indicate that the series for annual runoff were locally maximized in the 24th year. The results imply that there was a 24-year cycle for annual runoff over the study period of 1959–2005, which represented a periodic pattern concealed in the temporal fluctuation of the runoff in the Hotan River.

What caused the occurrence of such periodic runoff pattern in the Hotan River? Because the mainstream of the Hotan River is located in the arid area of Tarim basin that does not generate any volume, and its stream flow primarily comes from the two headwaters, i. e. the Karakash and Yulongkash River, which are in turn fed by glacier melt and snow melt in the Kunlun Mountains. The climate change in the headstreams directly affects the change of runoff in the Hotan River. Therefore, the underlying causes that drove the periodicity of runoff in the Hotan River may be some relevant climatic factors. So, it is necessary to analyze the correlation between the runoff of the Hotan River and the regional climatic factors, and to determine whether there is a similar cyclic pattern with runoff in the related variables. For this reason, Sect. 3.2 and Sect. 3.3 are arranged to discuss the problems in this paper.

3.1.2 Nonlinear trend of runoff depended on the time-scale

The nonlinear trends for the runoff process were analyzed at multiple-time scales through wavelet decomposition on the basis of the discrete wavelet transform (DWT).

The wavelet decomposition for the time series of annual runoff in the Hotan River at five time scales resulted in five variants of nonlinear trends (Fig. 4). At the time scale of 2-year, the S1 curve retains a large amount of residual noise from the raw data (see Fig. 2 for a comparison), and drastic fluctuations with 7 peaks and 7 valleys along the entire time span. These characteristics indicate that, although the total runoff from the two headwaters (i.e. the KaraKash and Yulongkash River) varied greatly throughout the study period, there was a hidden decreasing trend. At the time scale of 4-year, the S2 curve still retains a considerable amount of residual noise, as indicated by the presence of 3 peaks and 3 valleys. However, the S2 curve is much smoother than the S1 curve, which allows the hidden decreasing trend to be more apparent. At the time scale of 8-year, the S3 curve retains much less residual noise, as indicated by the presence of one peak and two valleys. Compared to S2, the decrease in runoff over time was more apparent in S3. Perceptibly, the decreasing trend is more obvious in the S4 curve at the time scale of 16-year than in the S3 curve. Finally, the S5 curve at the time scale of 32-year presents a clear downtrend.

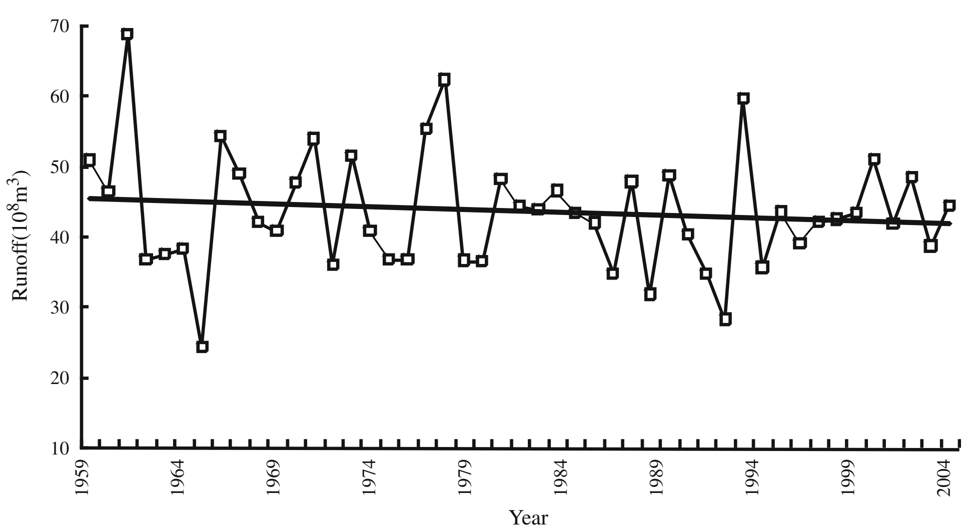

Fig. 2 The time series of annual runoff of the Hotan River

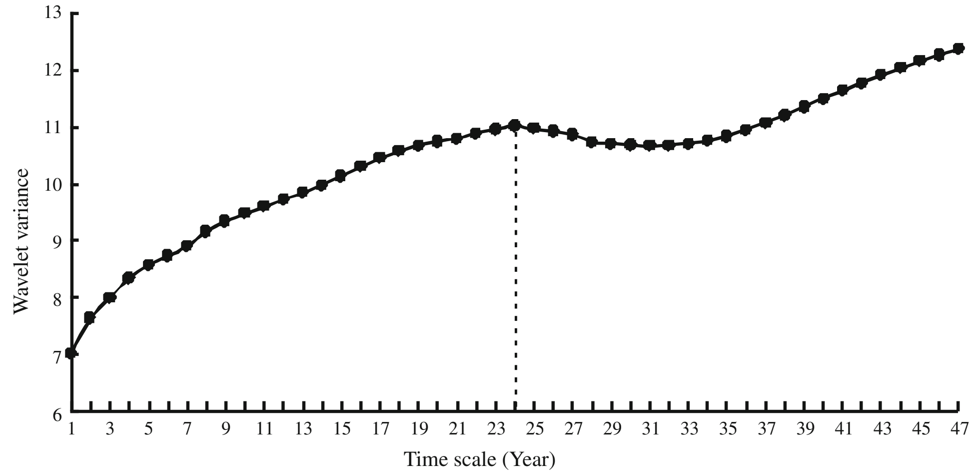

Fig. 3 Wavelet variances of annual runoff of the Hotan River

3.2 The correlation between the runoff and the relevant climatic factors

Some studies have shown that stream flows can also be influenced by other variables (called exogenous variables in time series analysis), such as matter and energy, and those influences might not be constants (Chen and Kumar 2004; Shao et al. 2009). Temperature and precipitation are the two main exogenous variables that respectively denote the input of matter and that of energy to surface hydrological system (Xu et al. 2010b).

Originating from the Kunlun Mountains, the Hotan River is mainly recharged by glacier melt and snowmelt, and the climate factors directly affecting the recharge of the river are temperature and precipitation. In the physical mechanism, the temperature mainly influences the runoff by glacier melt and snowmelt while precipitation supplies directly to the glaciers, snow cover and runoff (Archer and Fowler 2008; Li et al. 2008). Therefore, the above phenomena for the increasing trend of stream flow in the Hotan River whereas the decreasing trend of temperature and precipitation may be a false appearance. So, we cannot help asking the question: are there any correlations between stream flow and the climatic factors?

To answer the questions, we computed the correlation coefficient matrix for annual runoff in the Hotan River, the annual average temperature, annual precipitation in the Hotan area, and the 0°C level height in summer on the northern slope of the Kunlun Mountains. The results are listed in Table 2.

Table 2 tells us there is almost no correlation between annual runoff and annual average temperature, and a little negative correlation between annual runoff and annual precipitation. It is evident that the results are illogical. As a commonly knowledge, higher temperature can melt more glacier and snow, and more precipitation can generate more snow and surface runoff certainly. Therefore, there should be positive correlation between runoff and

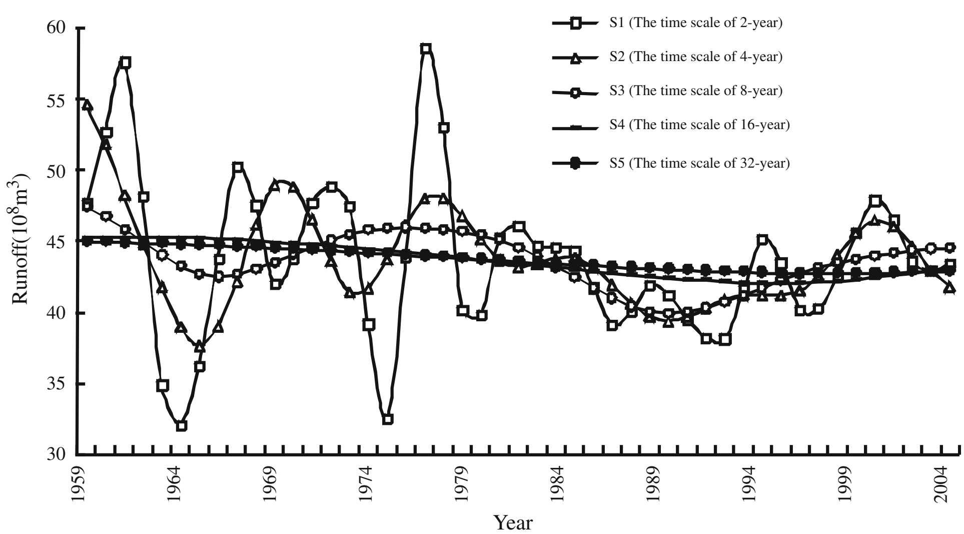

Fig. 4 Wavelet approximations for the annual runoff of the Hotan River at different year-scales

Table 2 The correlation coefficient matrix for runoff, temperature, precipitation and the 0°C level height in summer

	Annual runoff	Annual average temperature	Annual precipitation	The 0°C level height in summer
Annual runoff	1			
Annual average temperature	0.08588*	1		
Annual precipitation	−0.19887*	−0.17574*	1	
The 0°C level height in summer	0.62428**	−0.025097*	−0.51912**	1

* Means that the correlation coefficient did not pass the significance test at the significant level of 0.1

** Means that the correlation coefficient pass the significance test at the significant level of 0.001

temperature and precipitation. This conclusion has already been proved by the other headwaters of the Tarim River, i.e. the Yarkand, Aksu, and Kaidu River (Lu et al. 2010; Xu et al. 2010b, 2008b).

What is the cause of the paradox for the Hotan River? This is due to the special geographical location of the Hotan River. Among the four headwaters of the Tarim River, the Yarkand River originates from the Pamir Mountains, and the Aksu and Kaidu River originate from the Tianshan Mountains, whereas the Hotan River originates from high Kunlun Mountains. The snow line in Kunlun Mountains towers 2,500 m above that in Tianshan Mountains, and 1,500 m above that in the Parmir Mountains (Shi 2005). Therefore, the data from the ground meteorological stations in the Hotan area did not measure the climatic characterization in the high Kunlun Mountains. Thus, we should find the causes for runoff change of the Hotan River in the high Kunlun Mountains area.

3.3 The relationship between the runoff and the 0°C level height in summer

In fact, over the past few decades, against the general warming in Northwest China, some local regions still appeared cooling trend. In the temperature change map of China in recent 50 years drawn by Ren et al. (2005), there is a 0.4–0.6°C cooling zone in the central area from southern Xinjiang to the northern margin of Qinghai-Tibet Plateau in summer. Shi et al. (2006) deemed that there were exceptional cooling areas in the northern Qinghai-Tibet Plateau and Xinjiang region in the late twentieth century. It is evident that the glacier and snow melt must weaken in these exceptional cooling areas. Liu et al. (2006) showed that glacier retreating was the main trend in the Tarim River Basin, additionally there was also the forward phenomenon of glacier, and the more obvious in the Hotan River basin.

The ground meteorological data does not truly reflect the climate change in the high mountain area, and we don't have data for none of ground meteorological station in Kunlun Mountains. How can we find the cause of the nonlinear trend of the runoff for the Hotan River? We noticed the information in Table 2 that the stream flow of Hotan River is significantly correlated with the 0°C level height in summer on the northern slope of the Kunlun Mountains, which should indicate information of the glaciers and snow melt in the originating area of the Hotan River. This information corresponds to the investigations by Zhang et al. (2005) and Wang et al. (2008); they indicated that the 0°C level height in the summer on the north slope of the Kunlun Mountains has showed a downward trend in volatility in the past few decades. Therefore, we can use the data of 0°C level height in summer on the north slope of the Kunlun Mountains, and check its consistency in change with the runoff of Hotan River.

3.3.1 The same periodicity of the 0°C level height in summer and runoff

Using the average data of 0°C level height in summer from 4 air sounding meteorological stations on the north slope of Kunlun Mountains, we computed the wavelet variances (see Fig. 5) as the method above. Figure 5 tells us that the series for the average height of 0°C level in summer locally maximized in the 24th year. The results imply that there was a 24-year cycle for the average height of 0°C level in summer on the north slope of Kunlun Mountains over the study period of 1959–2005, which corresponds to change cycle for the runoff of Hotan River. In other words, the annual runoff of Hotan River and the average height of 0°C level in summer on the north slope of Kunlun Mountains present a same periodicity, i.e. 24-year cycle in change.

3.3.2 The similar nonlinear trends of the 0°C level height in summer and runoff

Using the wavelet decomposition method as above, we found that the average height of 0°C level in summer on the north slope of Kunlun Mountains presented nonlinear trends depended on time scales, which is similar to that of the runoff process. Figure 6 shows that the nonlinear trends depend on different year-scales. At the time scale of 2-year,

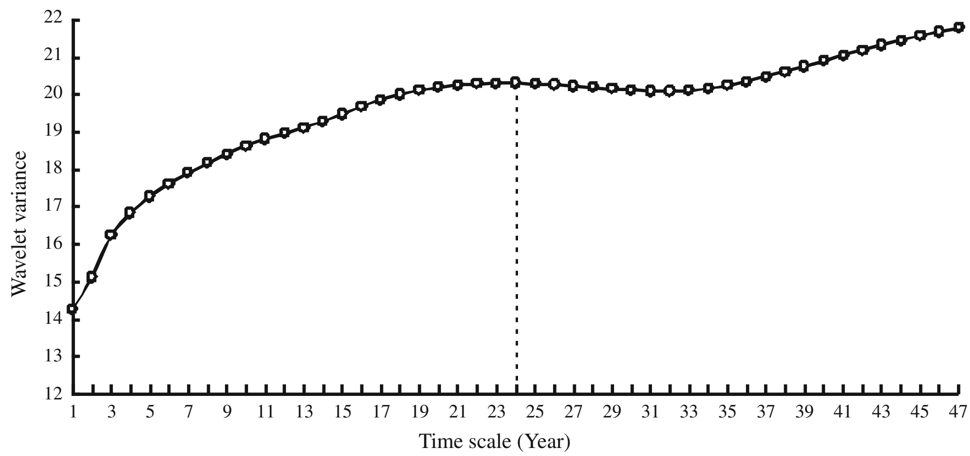

Fig. 5 Wavelet variances of the 0°C level height in summer on the north slope of Kunlun Mountains

the S1 curve presents drastic fluctuations with 8 peaks and 7 valleys along the entire time span as it retains a large amount of residual noise from the raw data. At the time scale of 4-year, the S2 curve still retains a considerable amount of residual noise, as indicated by the presence of 4 peaks and 4 valleys. However, the S2 curve is much smoother than the S1 curve, which allows the hidden decreasing trend to be more apparent. The S3 curve at the time scale of 8-year is much smoother than the S2 curve at the time scale of 4-year. Subsequently, the S4 curve at the time scale of 16-year only appears one peak and one valley, which accentuates the hidden decreasing trend. Finally, at the time scale of 32-year, the S5 curve presents a clear downtrend. The similar nonlinear trends indicate that the average height of 0°C level in summer on the north slope of Kunlun Mountains corresponds to annual runoff of the Hotan River.

3.3.3 *Significant correlations between the 0°C level height in summer and runoff*

The same cycle in change periodicity and similar nonlinear trends at different time scales indicate that there may be a correlation between the runoff of Hotan River and the average height of 0°C level in summer on the north slope of Kunlun Mountains.

Based on the results of wavelet decomposition at different time scales, we fitted the regression equations for describing the correlations between the annual runoff of Hotan River and the average height of 0°C level in summer on the north slope of Kunlun Mountains (see Table 3).

The regression at S3 (i.e. the time scale of 8-year) is not significant, and the reason for this may be the wavelet decomposition at this middle scale neither approximate the long term trend nor feedback for details of the two

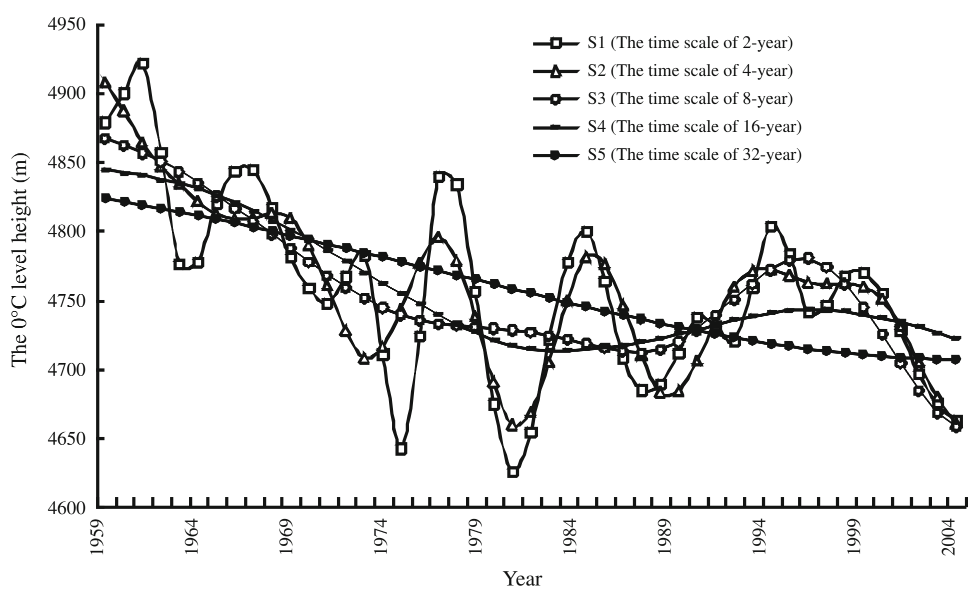

Fig. 6 Wavelet approximations for the 0°C level height in summer on the north slope of Kunlun Mountains at different year-scales

Table 3 The correlations between the annual runoff of Hotan River and the 0°C level height in summer on the north slope of Kunlun Mountains at different time scales

Time scale	Regression equation	R^2	F	Significance level α
S0	AR = −219.417 + 0.05532*H	0.3897	29.3761	0.000
S1	AR = −158.684 + 0.0425*H	0.2844	18.2834	0.000
S2	AR = −75.5124 + 0.02486*H	0.1878	10.6343	0.002
S3	AR = −1.9629 + 0.0096*H	0.0686	3.3893	0.072
S4	AR = −56.6698 + 0.0211*H	0.5792	63.3254	0.000
S5	AR = −41.677 + 0.01796*H	0.9790	2146.821	0.000

AR the annual runoff of the Hotan river; *H* the 0°C level height in summer on the north slope of the Kunlun Mountains

variables. Except the regression equation at S3, all other regression equations at S0, S1, S2, S4, and S5 (i.e. at the time scale of 1, 2, 4, 16, and 32-year) are highly significant, which indicate that the annual runoff of Hotan River is significantly correlated to the 0°C level height in summer at the time scale of 1, 2, 4, 16, and 32-year, respectively. These results indirectly tell us that the change trends of the annual runoff for the Hotan River are consistent with the change of the 0°C level height in summer on the north slope of Kunlun Mountains, and also illustrate that the runoff of Hotan River is mainly from melting glaciers and snow, and highly concentrated in summer.

4 Conclusions

Summarizing the above results and discussion, we elicited the basic conclusions as follows: due to the special geographical location and the headstream's differences from the other three headwaters of the Tarim River (i.e. the Yarkand, Aksu, and Kaidu River), the runoff pattern in the Hotan River is different from the other three headwaters of the Tarim River, which shows a periodicity and slight decrease trend with nonlinear fluctuations at different time scales. Although the data from the ground meteorological stations appeared a false phenomenon, i.e. temperature and precipitation slightly increased whereas the runoff slightly decreased, the data from air sounding meteorological stations showed reasonable explanations, i.e. there is a close relation between the 0°C level height in summer and the runoff. The two variables, the 0°C level height in summer and the runoff present a same periodicity, having similar nonlinear trends and significant correlations at different time scales. That is to say, hydro-climatic process in the Hotan River is not an exception, and its runoff change is related with the regional climate change, especially with the temperature change in its headstream.

The main findings of this study are as follows:

1. The hydrological process of the Hotan River represented by the annual runoff time series over the 47 years from 1959 to 2005 is a nonlinear system, which appeared a periodicity of 24 year cycle and presented different nonlinear trends at the time scale of 1, 2, 4, 8, 16, and 32-year.
2. The data from the ground meteorological stations in the Hotan area shows that there is almost no correlation between runoff and temperature, and a little negative correlation between runoff and precipitation. This abnormal appearance resulted from the data from the ground meteorological stations. Because the runoff of Hotan River concentrates in summer and mainly comes from the glaciers and snowmelt in the high Kunlun Mountains, the data from the ground meteorological stations in the Hotan area do not truly reflect the climate change in high mountains.
3. The nonlinear trend of runoff in the Hotan River during the past few decades was indeed related with the regional climate change, especially with the temperature change; however, the region here does not refer to the Hotan area but the originating area of the Hotan River in the Kunlun Mountain areas. This conclusion is indirectly supported by the following details: (a) the annual runoff of Hotan River and the 0°C level height in summer on the north slope of Kunlun Mountains present a same periodicity, i.e. 24-year cycle in change; (b) the similar nonlinear trends of the annual runoff of Hotan River corresponding to the 0°C level height in summer on the north slope of Kunlun Mountains; and (c) the annual runoff of Hotan River is significantly correlated to the 0°C level height in summer on the north slope of Kunlun Mountains at the time scale of 1, 2, 4, 16, and 32-year respectively.

Based on the data from hydrological stations, ground and air sounding meteorological stations, this study applied an integrated method to investigate the nonlinear trend of runoff in the Hotan River with its relevant climatic factors from a new perspective. But due to the complexity of hydro-climatic system coupled with the particularity of the geographical environment, it is difficult to thoroughly understand the nature of hydro-climatic process of the Hotan River basin. In fact, the methods used in this paper including correlation analysis, wavelet analysis and regression analysis are still statistical analysis methods, lacking of physical mechanism investigation. Therefore, we sincerely hope that better research methods and results will be proposed to complement insufficient understanding the nonlinear trend of runoff in the Hotan River and its causes.

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