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The nonlinear trend of runoff and its response to climate change in the Aksu River, western China

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ABSTRACT: The nonlinear trend of runoff and its response to climate change in the Aksu River were identified and evaluated using several selected methods, including grey relation analysis, wavelet analysis, and regression analysis. The time series of runoff and related climate variables from two hydrologic stations and four meteorological stations during 1959–2005 for the Aksu River were used to construct and test empirical models. The key findings of this study indicate that although the time series of the runoff, temperature and precipitation present nonlinear trends, the runoff exhibits a linear correlation with the temperature and precipitation. These results reveal that there is a close relationship between variations in the annual runoff of the Aksu River and regional climate change; in other words, the nonlinear trend of the variations in the runoff is the response to that of regional climate change. The details supporting the key findings are as follows: (1) The annual runoff presented nonlinear trends that depend on time scales, which appeared to have resulted from the regional climate changes that occurred during the study period. (2) The periodicity of changes in runoff, temperature, and precipitation are closely correlated, that of annual runoff occurred on 24-year cycle, whereas annual average temperature and annual precipitation occurred on 23- and 25-year cycles. (3) The annual runoff exhibited a significant, positive correlation with the temperature and precipitation at the 1-, 2-, 4-, and 8-year temporal scales.

KEY WORDS climate change; nonlinear trend; grey relation analysis; wavelet approximation; wavelet regression analysis; Aksu River; Northwest China

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1. Introduction

In the last 20 years, many studies have been conducted to evaluate climate change and the hydrological processes in the arid and semi-arid regions in northwestern China. A number of studies (Chen and Xu, 2005; Chen *et al*., 2006; Wang *et al*., 2006; Shi *et al*., 2007) have indicated that there was a salient turning point in the hydrological and climatic processes of the region after the 1980s. This new trend was characterized by a continual increase in temperature and precipitation, added river runoff volumes, increased lake water surface elevation and area, and elevated groundwater levels. These changes have led to increased water resources, providing immediate relief to the local water shortage. However, the climate change has also caused the accelerated retreat of glaciers, which are important natural water reservoirs for the delta ecosystems in inland China. This phenomenon has raised widespread concerns worldwide and recently has become a hot topic in related academic fields.

However, it has proven difficult to achieve a thorough understanding of the nonlinear mechanism of any individual hydroclimatic process (Cannon and McKendry, 2002; Xu *et al*., 2008a, 2008b). Specifically, there is still a lack of effective means available to reveal the type of nonlinearity underlying hydroclimatic process. Theoretically, hydroclimatic process can be evaluated to determine if they comprise an ordered, deterministic system, an unordered, random system, or a chaotic, dynamic system, and whether change patterns of periodicity or quasi-periodicity exist. Specific to the series of climate changes that have occurred in the arid/semi-arid region of western China, such inquiries may be designed to determine if these changes represent a localized transition to a warm and wet climate type in response to global warming, or merely reflect a centennial periodicity in hydrological dynamics. To date, these questions have not received satisfactory answers; therefore, more studies are required to explore the nonlinear characteristics of hydroclimatic process from different perspectives and using different methods (Xu *et al*., 2009a, 2010).

For mountainous river in arid area of Northwest China, such as the Aksu River, one of headwaters of the Tarim

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River, which has been relatively undisturbed by human activities, is mainly recharged by rainfall, seasonal glacier melt and snowmelt, and the climate factors directly affecting the recharge of the river are temperature and precipitation. From 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. Ahlmmann (1924) has proposed the method calculating the amount of snowmelt above the glacier equilibrium-line height using the data describing temperature; thereafter, Khodakov (1965) and Krenke (Krenke and Khodakov, 1966) further developed this approach. Kang and Ohmura (1994) also believed that the equilibrium line could be used as a standard position to estimate the amount of glacier melt. However, this approach representing an average state ignored the glacier melting intensity varying with height. Regarding the calculations for glacier melt runoff, Moore (1993) has proposed a structural model. The model divided the basin into several height zones and each zone was dealt with separately according to glacier area and non-glacial areas. The basic inputs were average temperature and precipitation of each zone with a daily time step and the outputs were runoff and evaporation of the glacier areas. But the mechanism of the model was still not well understood as it not only overlooked the infiltration of water, but also ignored the variation of parameters in space; therefore it still belonged to a lumped conceptual hydrological model. Then, there was a physics-based distributed hydrological model considering in depth about the impact on hydrological cycle from the uneven spatial distribution in watershed underlying surface (Singh and Woolhiser, 2002; Githui *et al*., 2009). It divided the basin into many grids and sub-basins in horizontal and layers the soil in vertical, simultaneously, and it applied some differential equations in physical and hydraulic to solve the temporal and spatial variation of runoff, according to the characteristics of runoff formation and affluxion in basin. The advantage was significant when compared to the traditional lumped conceptual hydrological model of the basin. But for the mountainous basin covered with snow and glaciers, it is still difficult 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 hydroclimatic process (Xu *et al*., 2008b, 2009b).

For the above reasons, we neither involved complex physical mechanisms nor used traditional statistical analysis. Based on the observed climatic and hydrological data series from two hydrologic stations and four meteorological stations, this study applied several selected methods, including grey relation analysis, wavelet analysis, and regression analysis to investigate the nonlinear trends of runoff and its response to regional climate changes in the Aksu River.

2. Materials and methods

2.1. Study area

The Aksu River is the largest runoff of the rivers located on the south slope of the Tianshan Mountains and lies in the northwest edge of the Tarim Basin, which is enclosed between latitudes 40°17′–42°27′N and longitudes 75°35′–80°59′E (Figure 1) covering a basin area of 5.14×10^4 km^2. The terrain declined gradually from north to south and from west to east, with distinct geomorphological zoning from high to low, which are low-middle mountain and hill, group of piedmont pluvial fans, tilted alluvial-proluvial plain, and alluvial plain(elevation of 1000–1500m) in turn. Due to the special geographical location of inland and far away from sea, the Aksu River drainage 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. The multi-year average temperature, precipitation, evaporation in the drainage, respectively, are 9.2–11.5 °C, 64 mm, 1890 mm; annual extreme maximum and minimum temperature is 40.2 and −27.6 °C; and the multi-year mean sunshine duration is 2850 h. The two main tributaries, the Kumalak and Toxkan River, join at Kaladuwei before flowing into the Aksu River. The catchment area of Kumalak, which is the north branch, is 12 816 km^2, and the length from its headwaters to the confluence point is 293 km, while that of Toxkan River, which is the west branch, are 18 400 km^2 and 457 km, respectively (Ding, 2007). Mountainous areas are the major areas of runoff generation for the Aksu River, and the runoff fluctuation is resulted from the complex climatic condition and hydrological environment.

2.2. Data

To evaluate the nonlinear trend in annual runoff in the Aksu River, the annual data from 1959 to 2005 for the two sub-rivers were used. The data were obtained from the Xiehela and Shaliguilank hydrologic stations (their locations were marked in Figure 1). Because the two stations are located in 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.

Long-term climate changes can alter the runoff production pattern, the timing of hydrological events, and the frequency and severity of floods, particularly in arid or semi-arid regions. Therefore, a small change in precipitation and temperature may result in marked changes in runoff (Gan, 2000). To investigate the relationship between the annual runoff and the regional climate change, this study used the monthly, quarterly, and annual data of temperature and precipitation from Akqi, Wushi, Aksu, and Baicheng meteorological stations (their locations were marked in Figure 1) for the same study period.

2.3. Methodology

In order to identify and understand the different aspects of nonlinear trends of the annual runoff and its response

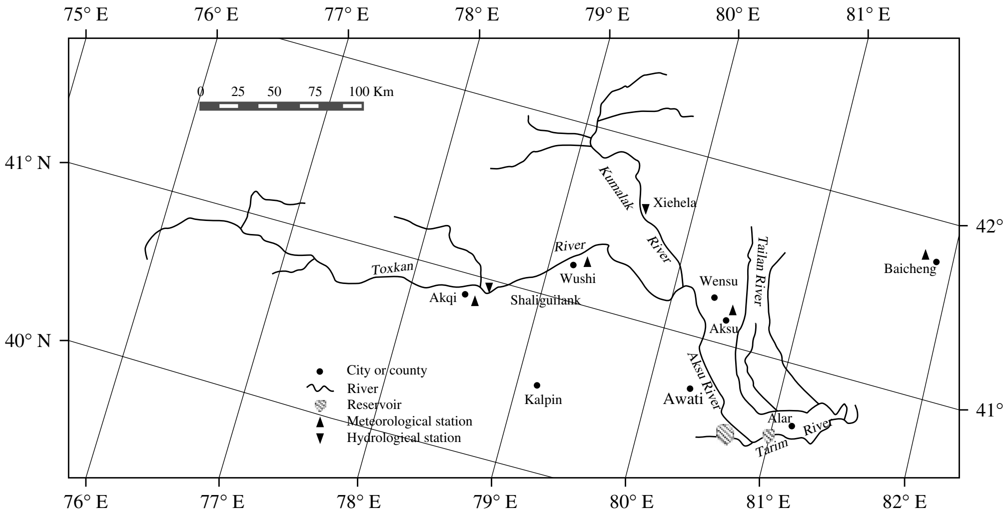

Figure 1. Location of the Aksu River.

to regional climate change, this paper conducted a comprehensive method including the grey relation analysis, wavelet analysis, and multiple regression analysis. First, the grey relation analysis method was used to rank climate factors and select the most important variables which affect the stream flow. Secondly, wavelet analysis was used to reveal the periodicity and nonlinear change trends of runoff and the related climate factors. Thirdly, based on the results of wavelet analysis, the response of the annual runoff to climate factors was revealed by using the multiple regression analysis method.

2.3.1. Grey relation analysis

Stream flow is related to many climatic factors, which is a very complicated system and relationship between climate and stream flow are not well known. From the point of grey system theory (Deng, 1989), the hydroclimatic process of Aksu River is a typical grey system (Xu, 2002). The grey relation analysis method was used to select most important climate factors affecting the stream flow. In a grey relation analysis, variables of time series are represented as reference series and influence series. The grey relation is the indefinite relationship among the two types of time series data, and the aim here is to compute the affecting degree of influence series to reference series. A parameter called grey relation degree is used to represent propinquity of two series. If the relation degree of one series is higher than that of others, this particular series is deemed to place greater influence on the reference series, and will be chosen for modelling (Deng, 1985).

The principle of grey relation analysis is as follows. For reference series $\{X_1(t),\ t = 1,\ 2,\ \ldots\ldots\}$, i.e. runoff, and influence series $\{X_i(t),\ i = 1,\ 2,\ldots;\ t = 1,\ 2,\ \ldots\ldots\}$, i.e. annual precipitation, precipitation in flood season, average annual temperature, etc., the following formula is used to calculate relation parameters of two series (Deng, 1985):

$$\xi_{1i}(t) = \frac{\min\limits_{i}\min\limits_{t}|X_1(t) - X_i(t)| + k\max\limits_{i}\max\limits_{t}|X_1(t) - X_i(t)|}{|X_1(t) - X_i(t)| + k\max\limits_{i}\max\limits_{t}|X_1(t) - X_i(t)|} \quad (1)$$

Where k is a grey parameter with a value range between 0 and 1, and often assigned a value of 0.5 for calculation.

With the computed relation parameters, we can calculate the grey relation degree of each influence series $(X_i(t))$ to reference series $(X_1(t))$:

$$\gamma_{1i} = \frac{1}{n}\sum_{t=1}^{n}\xi_{1i}(t) \quad (2)$$

It needs to be pointed out that the data of each series should be normalized before conducting the grey relation analysis. There are several methods for normalizing the data, and this paper uses one as follows:

$$x_i(t) = \frac{X_i(t) - \min\limits_{t}\ X_i(t)}{\max\ X_i(t) - \min\limits_{t}\ X_i(t)} \quad i = 1, 2, \ldots, m \quad (3)$$

That is to say, $x_i(t)$, instead of $X_i(t)$, should be used in Equation (1) for computation.

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 (Torrence and Compo, 1998; Smith *et al*., 1998; Chou, 2007; Xu *et al*., 2008a, 2008b). 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.

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

$$\Psi(\eta) = \Psi(a, b) = |a|^{-1/2}\Psi(\frac{t-b}{a}) \quad (4)$$

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 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 $\Psi(\eta)$,

$$W_x(a, b) = |a|^{-1/2} \int_{-\infty}^{+\infty} x(t)\Psi^*(\frac{t-b}{a})dt \quad (5)$$

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:

$$W_x(a) = \int_{-\infty}^{+\infty} |W_x(a, b)|^2 db \quad (6)$$

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 analysed 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):

$$x(t) = \sum_k \mu_{j_0,k}\phi_{j_0,k}(t) + \sum_{j=1}^{j_0}\sum_k \omega_{j,k}\psi_{j,k}(t) \quad (7)$$

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 behaviour (detail) from the large-scale behaviour (approximation) of the signal (Bruce *et al.*, 2002). The relationship between scale and signal behaviour 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 $a = 2, 4, 8, \ldots\ldots$, 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 hydroclimatic process of Aksu River is a nonlinear system because of the complex geographical and environmental background, maybe it is difficult to establish the statistical relationship between runoff and climate factors as it was commonly done in many other researches (Hastenrath, 1990; Xu, 2002; Lee and Chung, 2007; Chen *et al.*, 2009). For understanding the response of the runoff to regional climate change, this paper also conducted a wavelet regression analysis to examine the response of the runoff to climate change. The analysis step is as follows (Xu et *al.*, 2008b): (1) first, nonlinear trends of runoff and climate factors, such as annual runoff, annual average temperature, and annual precipitation were approximated by using wavelet decomposition on the basis of the DWT at different time scales; (2) then, the statistical relationship between runoff and temperature and precipitation were revealed by using regression analysis method based on the wavelet approximation.

3. Results and discussion

3.1. Ranking of climate factors in order of importance

As one of the main tributaries of the Aksu River, the Kumalak River is supplied primarily by alpine ice-snowmelt water, and the river flow has increased rapidly since May, reaches the maximum in August, thereafter it begins to decrease rapidly in September. The Toxkan River is supplied by alpine ice-snowmelt, rainfall, and only a little seasonal snowmelt, with summer flood coming closely after spring flood between May and September. Basically, there is the same annual variation cycle for each tributary. Difference among inter-annual changes in seasonal runoff is significant. Specifically, runoff is less in winter and high in summer, accounting for over 60% of annual river discharge, with a maximum up to 80%, and autumn is also the high-flow season, taking up 15–30%.

As mentioned above, the Aksu River is supplied primarily by glacier–snowmelt and precipitation. Therefore, there are conceivably close relationships between runoff and a set of regional climate factors, especially temperature and precipitation. This perception is supported by the results of some previous studies for the headwaters of the Tarim River Basin (Xu *et al.*, 2004; Jiang *et al.*, 2005; Chen *et al.*, 2006; Zhang *et al.*, 2008; Xu *et al.*, 2009b). From the physical mechanism, the temperature mainly influences the runoff by glacier melt and snowmelt while

Table I. Grey relation degree between annual runoff and climate factors.

	AP	PFS	AAT	ATSP	ATSU	ATA	ATW
AR	0.6997	0.6520	0.7905	0.7532	0.7285	0.6241	0.6078
Order of grey relation degree	4	5	1	2	3	6	7

Notes: AR – annual runoff, AP – annual precipitation, PFS – precipitation in flood season, AAT – average annual temperature, ATSP – average temperature in spring, ATSU – average temperature in summer, ATA – average temperature in autumn, and ATW – average temperature in winter.

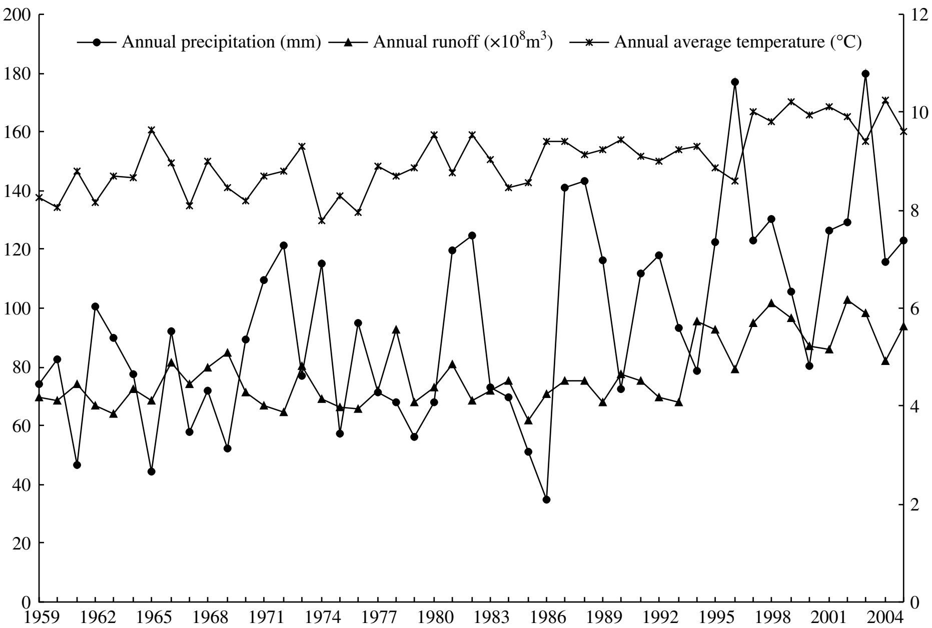

Figure 2. Original data of annual runoff, annual average temperature, and annual precipitation.

precipitation supplies directly to the glaciers, snow cover, and runoff. But the details of hydroclimatic process are very complicated system and lots of them have not known well by people. From the point of grey system theory, it is typical grey system. For this reason, it is necessary to investigate the effect of both precipitation and temperature on runoff. We checked the importance of each climate factor by calculating the grey relation degree for annual runoff (AR) with each of the influencing climate factors, including annual precipitation (AP), precipitation in flood season (PFS), average annual temperature (AAT), average temperature in spring (ATSP), average temperature in summer (ATSU), average temperature in autumn (ATA), and average temperature in winter (ATW). The results are shown in Table I.

Table I also provides a rank order of these climate factors with respect to their relative importance in predicting the runoff process. The average annual temperature seems to have the highest rank, followed by the average temperature in spring and then in summer. The annual precipitation and the precipitation in flood season take the fourth and fifth places, with the average temperature in the other two seasons being the last. When grouped, there is an obvious pattern showing that the average annual temperature and the annual precipitation are the leading climate factors that affect the annual runoff in this region. These two climate factors, therefore, were chosen as the representative factors in this study to be involved in the subsequent analyses.

3.2. Periodicity of runoff and climate change

The raw data of annual runoff, annual average temperature, and annual precipitation showed fluctuating patterns for the period of 1959–2005 (Figure 2). However, 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 a CWT.

Based on 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 (Figure 3) indicate that the series for annual runoff 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 represents a periodic pattern concealed in the temporal fluctuation of the runoff of the Aksu River.

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 that such influences might not be constants (Chen and Kumar, 2004; Shao *et al.*, 2009). Especially in

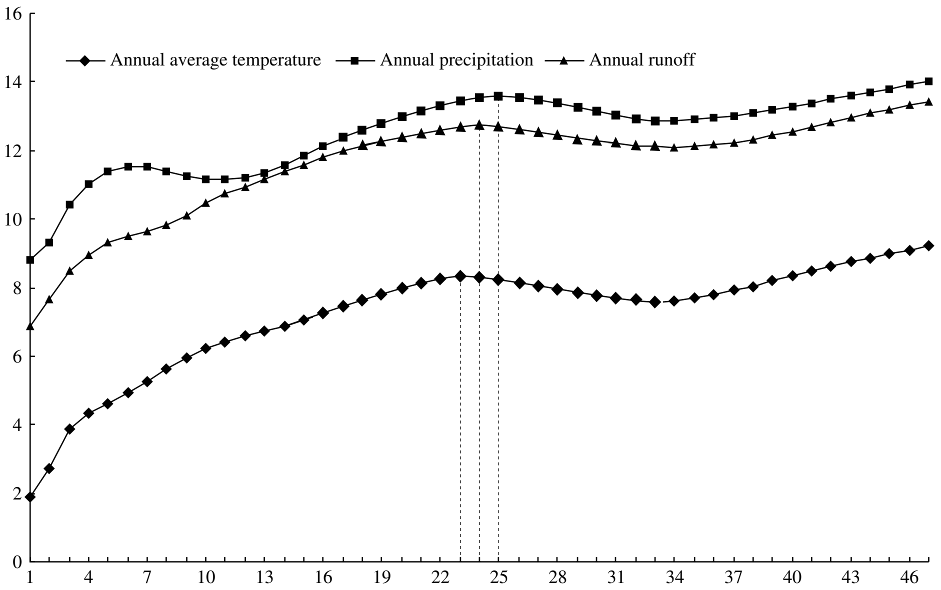

Figure 3. Wavelet variances of annual runoff, annual average temperature, and annual precipitation.

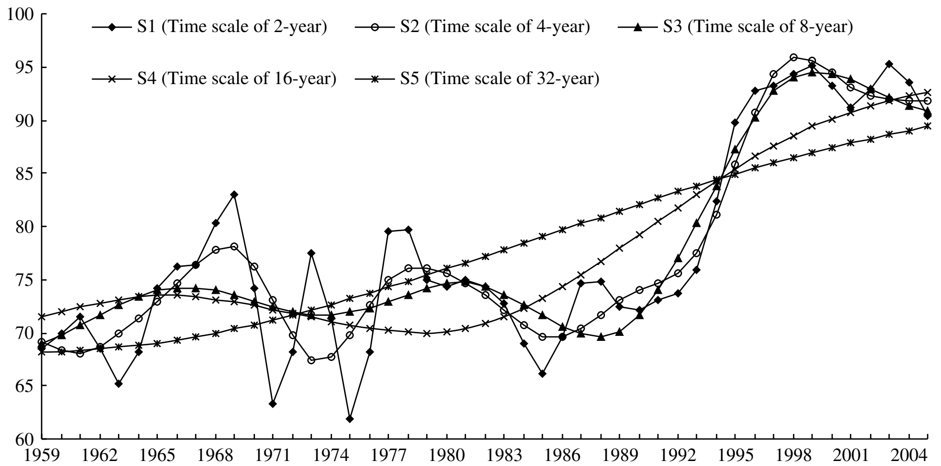

Figure 4. Nonlinear trends for annual runoff at the chosen time scales.

an arid inland river basin, the river flow mainly from mountainous watershed (Chen *et al*., 2008). Indeed, the runoff of the Aksu River primarily comes from the western Tianshan Mountain, which is in turn fed by snowmelt and precipitation in mountain area. Therefore, the dynamics of regional climate, especially temperature and precipitation, directly affect the annual changes in the runoff. For this reason, it is important to determine if there is a relationship in the time series of the annual runoff, annual average temperature, and annual precipitation during the study period. Accordingly, the wavelet variances were used to explore these two climate factors, and the computed results are also presented in Figure 3.

The computed wavelet variances (Figure 3) indicate that the series for annual average temperature and annual precipitation, the local maximum occurred in the 23rd year and 25th year, respectively. These results imply that there was a 24-year cycle for annual runoff, a 23-year cycle for annual average temperature, and a 25-year cycle for annual precipitation over the study period of 1959–2005, which represent a close periodic, i.e. rough 25-year cycle in the temporal fluctuation of them. By the way, we note that a small scale of 5-year cycle hides in the large scale of 25-year cycle for the annual precipitation over the period because there is the local maximum occurred in the 5th year on the curve of wavelet variances.

3.3. Nonlinear trend of runoff and climate factors

The nonlinear trend for the annual runoff process and the related climate factors were analysed at multiple-year scales through wavelet decomposition on the basis of the DWT.

The wavelet decomposition for the time series of annual runoff at five time scales resulted in five variants of nonlinear trends (Figure 4). The S1 curve retains a large amount of residual noise from the raw data (see

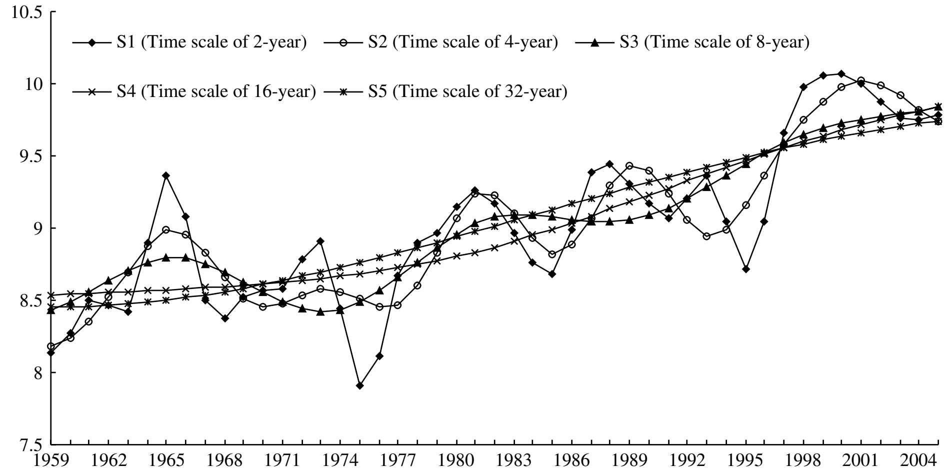

Figure 5. Nonlinear trends for annual average temperature at the chosen time scales.

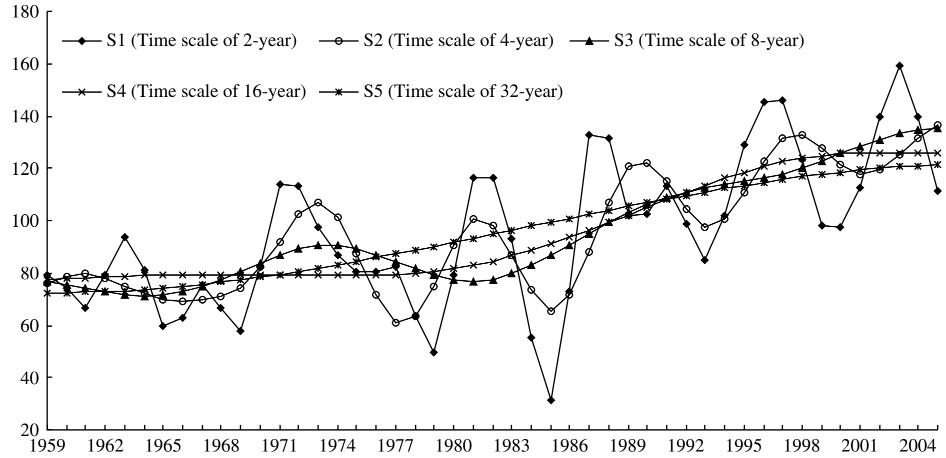

Figure 6. Nonlinear trends for annual precipitation at the chosen time scales.

Figure 2 for a comparison), and drastic fluctuations along the entire time span. These characteristics indicate that, although the runoff varied greatly throughout the study period, there was a hidden increasing trend. The S2 curve still retains a considerable amount of residual noise, as indicated by the presence of four peaks and three valleys. However, the S2 curve is much smoother than the S1 curve, which allows the hidden increasing trend to be more apparent. The S3 curve retained much less residual noise, as indicated by the presence of one peak and one valley. Compared to S2, the increase in runoff over time was more apparent in S3. Finally, the S5 curve presents an ascending tendency, whereas the increasing trend is obvious in the S4 curve.

Accordingly, Figures 5 and 6 provide us a method for comparing the nonlinear trends of annual average temperature and annual precipitation at different time scales. The wavelet decomposition for the time series of annual average temperature and annual precipitation at five time scales resulted in five variants of nonlinear trends, respectively. These five time scales are also designated as S1 through S5. The curves present an ascending tendency although drastic fluctuations in S1 and S2. Then, the curves are getting much smoother and the increasing trend becomes even more obvious as the scale level increases (see Figures 5 and 6 for a comparison). Therefore, the nonlinear trends of runoff, temperature, and precipitation of the Aksu River basin were found to be dependent on time scales.

3.4. The response of the runoff to climate change

The covariability between runoff and climate factors on multiple time scales can be examined via regression analysis based on the results of wavelet decomposition (Xu *et al.*, 2008b). To understand the response of the runoff to regional climate change, based on the results of wavelet decomposition at different time scales, regression equations were fitted for describing the relationship among annual runoff, annual average temperature, and annual precipitation (Table II).

The tabulated results (Table II) indicate that each regression model was statistically significant at $\alpha = 0.001$. However, the regression models produced by S0 through S3 yielded meaningful explanations in which the annual runoff was positively correlated with the annual average temperature and precipitation. Furthermore, the

Table II. Regression equations describing the relationship between annual runoff and annual average temperature and annual precipitation at different time scales.

Time scale	Regression equation	R^2	F	Significance level α
S0	$AR = 8.8150AAT + 0.0793AP - 9.6203$	0.3666	12.7340	0.001
S1	$AR = 10.7510AAT + 0.0742AP - 26.5651$	0.5765	29.9478	0.001
S2	$AR = 11.9308AAT + 0.0706AP - 36.9412$	0.6754	45.7753	0.001
S3	$AR = 11.4623AAT + 0.1397AP - 39.2254$	0.7991	87.5066	0.001
S4	$AR = -10.6715AAT + 0.6335AP + 113.1979$	0.9509	425.6954	0.001
S5	$AR = 25.6166AAT - 0.2411AP - 130.8705$	0.9999	1598.985	0.001

Notes: AR – annual runoff, AAT – annual average temperature, and AP – annual precipitation; S1, S2, S3, S4, and S5 represent 1-, 2-, 4-, 8-, 16-, and 32-year time scales, respectively.

regression models revealed a stronger relationship (i.e. a greater value for their partial regression coefficient) between runoff and temperature than between runoff and precipitation. These results provide further evidence supporting the view that the nonlinear ascending trend of the annual runoff time series is influenced by regional climate change. This findings are corresponding with the results of other studies (Chen and Xu, 2005; Chen *et al*., 2006), which have suggested that both the temperature and precipitation series in the Tarim basin have been increasing in a pattern similar to that of annual runoff over the past 50 years.

However, the regressions at S4 and S5 led to unreasonable results. The regression at S4 reveals a negative correlation between the runoff and the temperature, and that at S5 shows a negative correlation between the runoff and the precipitation, which do not seem reasonable. The unreasonable consequence is likely due to much information was lost in the wavelet decomposition of the time series runoff, annual average temperature and annual precipitation at S4 and S5.

The results suggest that although the time series of the runoff, temperature, and precipitation present nonlinear trends, the runoff has a linear correlation with the temperature and precipitation.

4. Conclusions

This paper applied several selected methods, including grey relation analysis, wavelet analysis, and regression analysis to reveal the relationship between the variations in runoff and climate changes of the Aksu River. The results suggest that there is a close relationship between the variations in runoff and regional climate changes of the Aksu River. The conclusions of this study include the following:

1. The hydrological processes of the Aksu River represented by the annual runoff time series over the 47 years considered in the study are nonlinear systems. Specifically, the processes have certain periodic, nonlinear trends at the selected time scales.
2. A cyclic period of 24 years was detected in the annual runoff time series of the Aksu River, while cyclic periods of 23 and 25 years were detected in the annual average temperature and annual precipitation, respectively. Therefore, the cyclic patterns of the runoffs and the regional climate factors are approximately in agreement. These results suggest that the periodicity of the annual runoff of the Aksu River is the result of regional climate changes.
3. The nonlinear runoff, temperature, and precipitation pattern of the Aksu River basin were found to be scale-dependent with respect to time. The wavelet decomposition for the time series of annual runoff, annual average temperature, and annual precipitation at five time scales resulted in five variants of nonlinear trends, respectively. The curves were getting much smoother and the increasing tendency became even more obvious as the time scales increased.
4. The time series of annual runoff varied markedly with the annual average temperature and annual precipitation. Furthermore, the runoff and the climate factors were significantly and positively correlated at 1-, 2-, 4-, and 8-year time scales. The results indicate that although the runoff, temperature, and precipitation present nonlinear trends, the runoff has a linear correlation with the temperature and precipitation.

From a new perspective, this paper has provided some conclusions for the response of the runoff process of the Aksu River to the climate change. But due to the complexity of hydroclimatic system coupled with the particularity of the geographical environment in the Aksu River basin, it is difficult to understand the nature of hydroclimatic process thoroughly. Exactly speaking, the methods including grey correlation, wavelet analysis, and regression analysis used in this paper are still statistical analysis methods, lacking physical mechanism investigated. Therefore, we sincerely hope that better research methods and results will be proposed to complement insufficient understanding in this paper.

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