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Long-term Trend and Fractal of Annual Runoff Process in Mainstream of Tarim River

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Abstract: Based on the time series data from the Aral hydrological station for the period of 1958–2005, the paper reveals the long-term trend and fractal of the annual runoff process in the mainstream of the Tarim River by using the wavelet analysis method and the fractal theory. The main conclusions are as follows: 1) From a large time scale point of view, i.e. the time scale of 16 (2^4) years, the annual runoff basically shows a slightly decreasing trend as a whole from 1958 to 2005. If the time scale is reduced to 8 (2^3) or 4 (2^2) years, the annual runoff still displays the basic trend as the large time scale, but it has fluctuated more obviously during the period. 2) The correlation dimension for the annual runoff process is 3.4307, non-integral, which indicates that the process has both fractal and chaotic characteristics. The correlation dimension is above 3, which means that at least four independent variables are needed to describe the dynamics of the annual runoff process. 3) The Hurst exponent for the first period (1958–1973) is 0.5036, which equals 0.5 approximately and indicates that the annual runoff process is in chaos. The Hurst exponents for the second (1974–1989) and third (1990–2005) periods are both greater than 0.50, which indicate that the annual runoff process showed a long-enduring characteristic in the two periods. The Hurst exponent for the period from 1990 to 2005 indicates that the annual runoff will show a slightly increasing trend in the 16 years after 2005.
Keywords: annual runoff; wavelet; fractal; Tarim River

1 Introduction

The Tarim River Basin, the largest continental river basin in China, is rich in natural resources, but has a vulnerable ecological environment. The conflict between ecological protection and economic development has become increasingly significant with respect to the utilization of water resources, and the sustainable development of the regional economy is therefore severely restricted by it (Chen and Xu, 2005; Chen et al., 2004).

The 1321-km Tarim River runs from west to east along the northern edge of the Taklimakan Desert, China's largest one, and flows into Taitmar Lake. The river is the most important source of water in semi-arid Xinjiang, with more than 8×10^6 people living in oases clustered along its banks and in its alluvial plain downstream. Yet, with the population increasing, due to excessive water use for irrigation, industrial and living consumption in the upper and middle reaches of the river, its downstream, which extends further down from the Daxihaizi Reservoir, has become completely dry ever since 1972. As a consequence, the ground-water depth in this area has lowered sharply and the ecosystem has been damaged seriously. Subsequently, many plant communities have gradually diminished or completely died away in the sequence of grass, shrub and tree (Li and Yang, 2001), and desertification in this region has become more and more aggravated (Chen et al., 2003). All of these indicated that the lower reaches of the Tarim River have serious ecological and environmental problems.

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Because the main available water resources of the Tarim River Basin is from runoff, which is mainly produced from glaciers, snowmelt and precipitation in the surrounding mountains, the streamflow trends and hydrological responses to climatic change of the river have received much attention. Some scholars argued that the discharge from the headwater of the Tarim River Basin had increased because of precipitation and air temperature increasing in the last century (Chen et al., 2006; Chen and Xu, 2005; Jiang et al., 2007), but the annual runoff in the mainstream of the river has tended to slight decrease in the past 50 years. The reasons for these phenomena may be water loss of streamflow (Wang and Hu, 2003) and purposeful water utilization for human activities (Li and Bao, 2003), such as water consumption for life, irrigation and industries, and water delivery.

From the point of view of complex system theory, the runoff process of the Tarim River is a complex system, which is nonlinear process (Smith et al., 1998; Wilcox et al., 1991). All statistical methods assume that all data of time series are independent (i.e. fit for Gauss distribution), hence the series is stochastic. When H E Hurst et al. analyzed water levels of the Nile River, he found that such time series of variables such as river water level were not fit for Gauss distribution, showing a characteristics of discontinuity and durability (Hurst, 1951; Hurst et al., 1965). Based on the empirical findings of Hurst, B B Mandelbrot made a breakthrough regarding fundamental theories of traditional statistical methods (Mandelbrot, 1973; Mandelbrot and Wallis, 1968) . He found many time series no longer present a random Brownian movement unrelated to the past, but show a characteristic of long-term correlation (Comte and Renault, 1996), which he called “fractal”.

In order to reveal the long-term trend and fractal of runoff process of the mainstream in the river basin, this paper reveals the trends of annual runoff at different time scales using wavelet analysis method, and shows the fractal and chaotic characteristics using the correlation dimension and R/S analysis method based on the time series data from Aral Hydrological Station for the period 1958–2005.

2 Materials and Methods

2.1 Study area

The Tarim River Basin, with an area of 1.02×10^6km^2, is the largest continental river basin in China. It covers the entire southern part of Xinjiang Uygur Autonomous Region in the western China, which is characterized by both rich natural resources and fragile environment, and has an extreme desert climate with an average annual temperature of 10.6℃–11.5℃. Monthly mean temperature ranges from 20℃ to 30℃ in July and –20℃ to –10℃ in January. The highest and lowest temperature is 43.6℃ and –27.5℃ respectively. The accumulative temperature >10℃ ranges from 4100℃ to 4300℃. Average annual precipitation is 116.8mm in the basin, and ranges from 200mm to 500mm in the mountainous area, 50mm to 80mm in the edges of the basin and only 17.4mm to 25.0mm in the central area of the basin. There is great unevenness in the precipitation distribution within any year. More than 80% of the total annual precipitation falls between May and September in the high-flow season, and less than 20% of the total falls from November to next April.

The main channel of the Tarim River is 1321km in length. Naturally and historically, the Tarim River Basin consists of 114 rivers from nine drainage systems, which include Aksu, Hotan, Yarkant, Qarqan, Keriya, Dina, Kaxgar, Kaidu and Konqi rivers. The basin has an arable land area of 20.44×10^6ha and a population of 8.26×10^6. Mean annual natural surface runoff is 39.8×10^9m^3, which originates mostly from glaciers, snowmelt and precipitation of the surrounding mountains.

Intensive disturbances caused by human activities, particularly excessive water resources exploitation, have brought about marked changes during the past 50 years. The drainage systems gradually disintegrated when the Weigan, Kaxgar, Dina, Keriya, and Qarqan rivers stopped supplying water to the Tarim River and were eventually disconnected from it. Today, there are only three drainage systems connected to the mainstream of the river. They are the Aksu River, the Yarkant River and the Hotan River. Having two main sub-streams, Tongshigan and Kumalak rivers, the Aksu River runs from the Tianshan Mountains in the northwest of the basin. The Hotan River, having two main sub-streams, the Karakax and Yulongkashi rivers, originates from the Kunlun Mountains and is located in the southwest of the basin. The Yarkant River originates from the Pamirs and lies between the Hotan and Aksu rivers (Fig. 1).

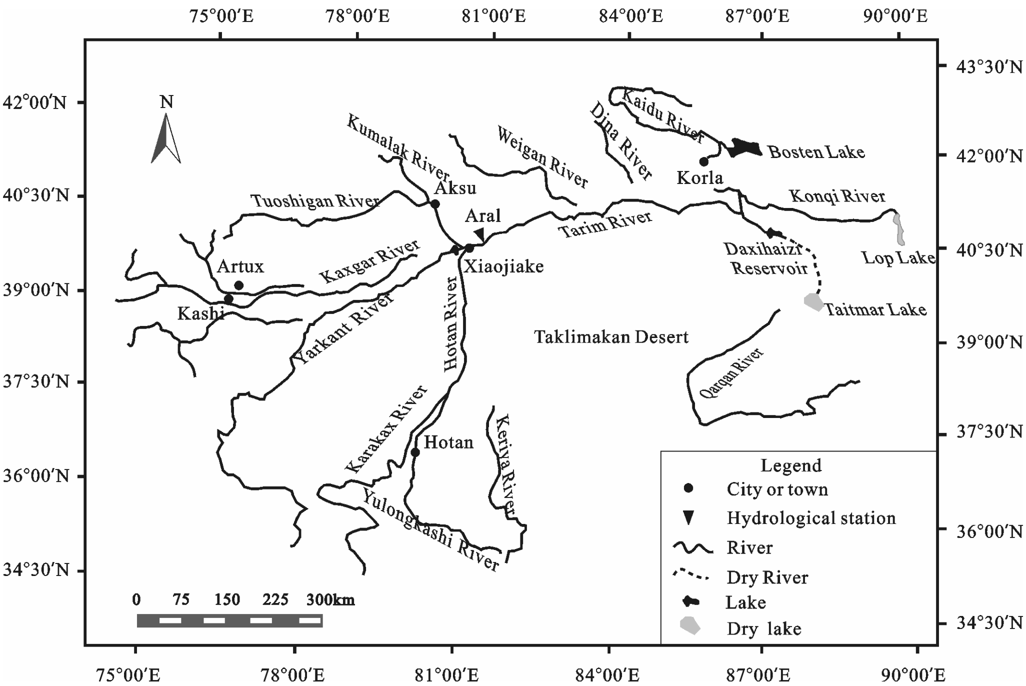

Fig. 1 Sketch map of Tarim River Basin

Glaciers, snowmelt and precipitation in the surrounding mountains are the sources of runoff of the Tarim River. Glacier meltwater and snowmelt make up 48.2% of the total runoff of the river. Inter-annual runoff variability is small, with a coefficient of variation ranging from 0.15 to 0.25 and the maximum and minimum modular coefficients of 1.36 and 0.79 respectively. Seasonal runoff is unevenly distributed. Runoff in the June–August flood season accounts for 60%–80% of the annual total (Chen et al., 2003).

2.2 Data

To analyze the long-term trend on the annual runoff in the mainstream of the Tarim River, the runoff data in the period of 1958–2005 from the Aral Hydrological Station were used. Because long-term climate change can alter the pattern of runoff production, the occurrence time of hydrological events and the frequency and severity of floods, particularly in arid or semi-arid regions, a small change in precipitation and temperature may result in marked changes in runoff (Gan, 2000). For such reasons, we used the annual runoff data to describe the runoff process in this study.

The annual runoff in the mainstream of the Tarim River from 1958 to 2005 is shown in Fig. 2.

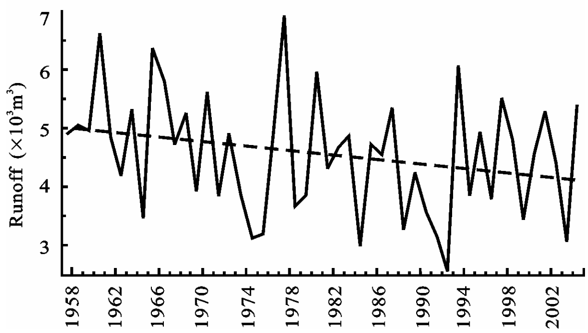

Fig. 2 Annual runoff in Aral hydrological station of Tarim River

2.3 Methodology

2.3.1 Wavelet analysis method

Wavelet analysis is a multi-resolution analytical approach, which is a way to analyze the time scales of signals (Xu et al., 2004). It may well be able to provide new insights into the periodicity of runoff processes (Smith et al., 1998). By using wavelet analysis, this paper will reveal the nonlinear trend of annual runoff process in the mainstream of the Tarim River at different time scales.

Considering the time series of annual runoff in a certain river $X(t)$, which can be built up, as a sequence of projections onto Father and Mother wavelets indexed by both $\{k\}$, $k=\{0, 1, 2, \ldots\}$ and by $\{s\}$, $s=2^j$, $\{j=1, 2, 3, \ldots\}$. The coefficients in the expansion are given by the equations

$$s_{J,k}=\int X(t)\Phi_{J,k}(t)\mathrm{d}t \tag{1}$$

$$d_{j,k}=\int X(t)\Psi_{j,k}(t)\mathrm{d}t,\ j=1, 2, ..., J \tag{2}$$

where J is the maximum scale sustainable by the number of data points, $\Phi_{J,k}=2^{-\frac{j}{2}}\Phi(\frac{t-2^j k}{2^j})$ is father wavelet, and $\Psi_{j,k}=2^{-\frac{j}{2}}\Psi(\frac{t-2^j k}{2^j})$ is mother wavelet. Generally, father wavelet is used for the lowest-frequency smooth components, which requires wavelet with the widest support; Mother wavelet is used for the highest-frequency detailed components. In other words, father wavelet is used for the trend components, and mother wavelet is used for all deviations from the trend. The representation of the signal $X(t)$ can be given by:

$$X(t)=\sum_k s_{J,k}\Phi_{J,k}(t)+\sum_k d_{J,k}\Psi_{J,k}(t)+\sum_k d_{J-1,k}\Psi_{J-1,k}(t)+...+\sum_k d_{1,k}\Psi_{1,k}(t) \tag{3}$$

We can represent the approximation in a more revealing manner for our purposes:

$$X(t)=S_J+D_J+D_{J-1}+...D_j+...+D_1 \tag{4}$$

where $S_J=\sum_k s_{J,k}\Phi_{J,k}(t)$ and $D_j=\sum_k d_{j,k}\Psi_{j,k}(t)$, $j=1, 2, \ldots, J$.

In general, we have

$$S_{j-1}=S_j+D_j \tag{5}$$

where $\{S_J, S_{J-1}, \ldots, S_1\}$ is a sequence of multi-resolution approximations of the function $X(t)$ at ever-increasing levels of refinement. The corresponding multi-resolution decomposition of $X(t)$ can be given by $\{S_J, D_J, D_{J-1}, \ldots, D_j, \ldots, D_1\}$.

One of our main interests of this research is to approximate the trends based on decomposition and reconstruction for the time series of annual runoff by using the above wavelet analysis method at different time scales. One of main objectives of this study is to examine the fluctuations for the time series of annual runoff in the mainstream of the Tarim River at different time scales, and to have an insight into the overall variation of the signal with time. We choose the Symmlet as the basic wavelet, designated 'Sym8'. We experimented with alternative choices of scaling functions and of wavelet, but the qualitative results were very robust to such changes and the initial choice of wavelet seemed to be the best on balance. In all cases, the levels analyzed are restricted to S4, S3, and S2 to represent the trend elements.

2.3.2 Fractal analysis method

In order to study the fractal characteristic of annual runoff processes in the mainstream of the Tarim River, the correlation dimension method and the rescaled range (R/S) analysis method are used in our research work.

(1) Correlation dimension. Consider $X(t)$, the time series of annual runoff in a certain river, and suppose which is generated by a nonlinear dynamical system with m degrees of freedom. In order to restore the dynamics characteristic of the original system, it is necessary to construct an appropriate series of state vectors $X^{(m)}(t)$ with delay coordinates in the m-dimensional phase space according to the basic ideas initiated by Packard et al. (1980):

$$X^{(m)}(t)=\{X(t), X(t+\tau), \cdots, X(t+(n-1)\tau)\} \tag{6}$$

where m is called the embedding dimension and τ is an appropriate time delay.

The trajectory in the phase space is defined as a sequence of m dimensional vectors. If the dynamics of the system is reducible to a set of deterministic laws, the trajectories of the system converge towards the subset of the phase space, which is called an "attractor". Many natural systems do not convert with time to a cyclic trajectory. Some nonlinear dissipative dynamical systems tend towards the attractors on which the motion is chaotic, i.e. not periodic and unpredictable over long times. The attractors of such systems are called strange attractors.

For the set $\{X_i \mid i=1, 2, \ldots, N\}$ of points on the attractor, using the G-P method (Grassberger and Procacia, 1983), the correlation-integrals is defined in order to distinguish between stochastic and chaotic behavior:

$$C(r)=\lim_{N\to\infty}\frac{1}{N^2}\ \{\text{Number of pairs }(i, j)\ \text{whose distance } |X_i-X_j|<r\} \tag{7}$$

where r is surveyor's rod for distance.

The correlation-integrals is computed as follows:

$$C(r)=\frac{1}{N_R^2}\sum_{j=1}^{N_R}\sum_{i=1}^{N_R}\Theta(r-|X_i-X_j|) \tag{8}$$

where, N_R is the number of reference points taken from N, and N is the number of points $X^{(m)}(t)$. The relationship between N and N_R is $N_R=N-(m-1)\tau$. $\Theta(x)$ is the Heaviside function such as:

$$\Theta(x)=\begin{cases}0 & x\le 0\\ 1 & x>0\end{cases} \quad (9)$$

The expression counts the number of points out of the data set, which are closer than radius r or within a hypersphere of radius r, and then divides it by the square of the total number of points (because of normalization). As $r\to 0$, the correlation exponent d is defined as:

$$C(r)\propto r^d \quad (10)$$

Apparently, the correlation exponent d is thus given by the slope coefficient of log$C(r)$ versus log(r). According to (log(r), log$C(r)$), d can be obtained by least squares method (LSM) in log-log grid.

For detecting the chaotic behavior of the system, the correlation exponent has to be plotted as a function of the embedding dimension. If $X^{(m)}(t)$ is purely random (e.g. white noise), the correlation exponent increases with the embedding dimension without reaching the saturation value.

If there is deterministic dynamics in the system, the correlation exponent reaches the saturation value: it remains approximately constant with an increase of the embedding dimension. The saturated correlation exponent is called the correlation dimension of the attractor. The correlation dimension belongs to the invariants of the motion on the attractor. It is generally assumed that it equals the number of degrees of freedom of the system and higher embedding dimensions are therefore redundant. For example, in order to describe the position of the point on the plane (two-dimensional system), the third dimension is not necessary—it is redundant. The correlation dimension is often fractal: it is the non-integral dimension, which is typical for the chaotic dynamical systems that are very sensitive to initial conditions.

The correlation dimension provides information on the dimension of the phase-space required for embedding the attractor. It is important for determining the number of dimensions necessary to embed the attractor and the number of variables present in evolution of the process.

(2) R/S analysis method. Considering the time series of annual runoff in a certain river, $X(t)$, for any positive integer $\tau\geq 1$, the mean value, accumulative deviation, extreme deviation and standard deviation are respectively defined as following:

$$\begin{aligned}
&\langle X\rangle_\tau=\frac{1}{\tau}\sum_{t=1}^{\tau}X(t) && \tau=1, 2, \cdots\\
&X(t,\tau)=\sum_{u=1}^{t}(X(u)-\langle X\rangle_\tau) && 1\le t\le\tau\\
&R(\tau)=\max_{1\le t\le\tau}X(t,\tau)-\min_{1\le t\le\tau}X(t,\tau) && \tau=1, 2, \cdots\\
&S(\tau)=\{\frac{1}{\tau}\sum_{t=1}^{\tau}[X(t,\tau)-\langle X\rangle_\tau]^2\}^{\frac{1}{2}} && \tau=1, 2, \cdots
\end{aligned} \quad (11)$$

When analyzing the statistic rule of $R(\tau)/S(\tau)\triangleq R/S$, H E Hurst discovered a relational expression:

$$R/S\propto(\tau/2)^H \quad (12)$$

which shows there is Hurst phenomenon in time series, and where H is called the Hurst exponent.

Apparently, the Hurst exponent H is given by the slope coefficient of R/S versus $\tau/2$. According to (τ, R/S), H can be obtained by least squares method (LSM) in a log-log grid.

Hurst et al. (1965) once proved that if $\{X(t)\}$ is an independently random series with limited variance, the exponent H=0.5; and H ($0<H<1$) is dependent on an incidence function $C(t)$:

$$C(t)=2^{2H-1}-1 \quad (13)$$

When $H>0.5$, $C(t)>0$, which means that the process has a long-enduring characteristic, and the future trend of the time series will be consistent with the past. In other words, if the past showed an increasing trend, the future will also show an increasing trend. When $H<0.5$, $C(t)<0$, which means that the process has an anti-persistence characteristic, and the future trend of the time series will be opposite from the past. In other words, if the past showed an increasing trend, the future will assume the reducing trend. When H=0.5, $C(t)$=0, which means that the process is stochastic. In other words, there is no correlation or only a short-range correlation in the process (Ai and Li, 1993).

3 Results and Discussion

3.1 Nonlinear trends of annual runoff

Based on decomposition and reconstruction for the time series by using the above wavelet analysis method at different time scales, we found that the nonlinear trends of the annual runoff process in the mainstream of the Tarim River are different at different time scales.

Figure 3 shows the wavelet approximation curves of the annual runoff in the mainstream of the Tarim River. At the time scale of S4, i.e. the time scale of 16 (2^4) years, the curve shows a local as well as the global minimum point appeared in 1989 with the value of $4.2865\times10^9m^3$. Though the annual runoff was firstly decreasing from 1958 to 1989 and then increasing slightly from 1989 to 2005, a basically decreasing trend can be clearly recognized as a whole from 1958 to 2005.

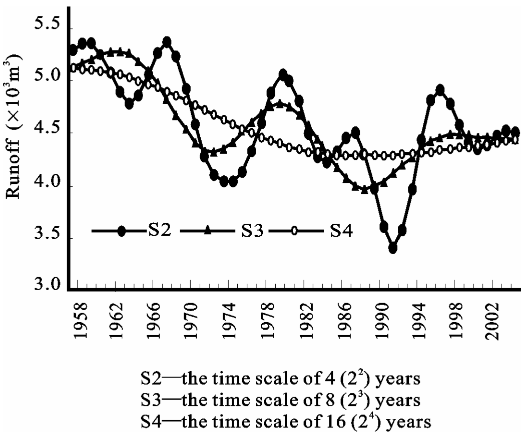

Fig. 3 Wavelet approximations for annual runoff at different time scales

If the time scale is reduced to S3, i.e. the time scale of 8 (2^3) years, the curve as a whole still presents the basic trend as that at the time scale of S4, but fluctuated obviously during the period. There are two local minima and three maximums on the curve, of which the two local minima appearred respectively in 1973 ($4.3242\times10^9m^3$) and 1989 ($3.9704\times10^9m^3$), the three local maximums appearred respectively in 1963 ($5.2867\times10^9m^3$), 1980 ($4.7895\times10^9m^3$) and 1999 ($4.4862\times10^9m^3$).

If the time scale is further reduced to S2, i.e. the time scale of 4 (2^2) years, though the curve as a whole still presents the basic trend as that at the time scale of S3, it has fluctuated more obviously during the period. There are five local minimum and maximum points on the curve, of which the five local minima appearred respectively in 1964 ($4.7830\times10^9m^3$), 1975 ($4.0461\times10^9m^3$), 1985 ($4.2289\times10^9m^3$), 1992 ($3.4079\times10^9m^3$), and 2001($4.3544\times10^9m^3$), the five local maximums appearred respectively in 1960 ($5.3617\times10^9m^3$), 1968 ($5.3727\times10^9m^3$), 1980 ($5.0507\times10^9m^3$), 1988($4.5061\times10^9m^3$), and 1997 ($4.9113\times10^9m^3$).

The results generally tell us that the annual runoff was decreasing from1958 to 1989, and increasing slightly from 1989 to 2005, but basically presented a decreasing trend as a whole from 1958 to 2005 at the time scale of 16 (2^4) years. If the time scale is reduced to 8 (2^3) or 4 (2^2) years, the annual runoff still displays the basic trend as a whole, but it has fluctuated obviously during the period.

3.2 Fractal and chaotic characteristics of annual runoff process

Figure 4a shows the relationship between ln*C*(*r*) versus ln(*r*) for the annual runoff in the mainstream of the Tarim River with different embedding dimension *m*. Using least square method (LSM), we calculated the slope coefficient of ln*C*(*r*) versus ln(*r*), i.e. the correlation exponent for embedding dimension *m*. It is evident that the correlation exponent increases versus embedding dimension *m*, but a saturated correlation exponent, i.e. the correlation dimension (D=3.4307) was obtained when $m\geq6$. Figure 4b reveals the gradually saturating process of the correlation exponent.

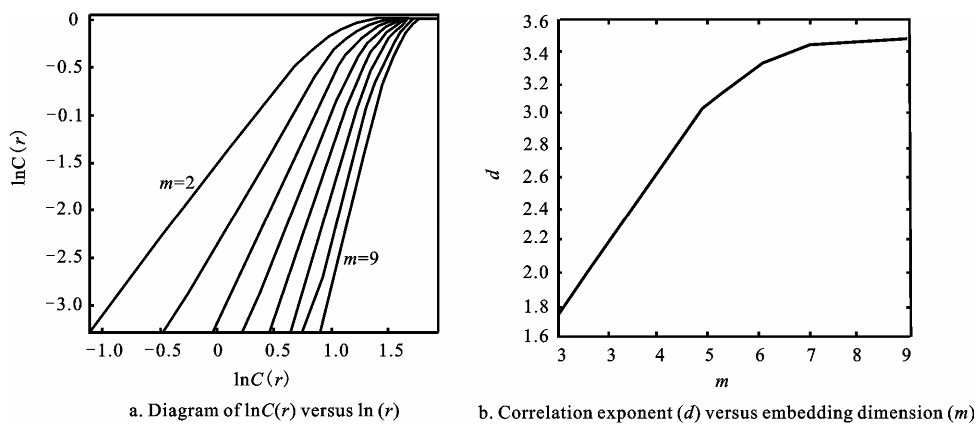

Fig. 4 Relationship between correlation exponent and embedding dimension

It is evident that the correlation dimension is non-integral, which indicates the annual runoff processes in the mainstream of the Tarim River has fractal and chaotic characteristics. The correlation dimensions are above 3, which mean that four independent variables at least are needed to describe the dynamics of annual runoff process in the mainstream of the Tarim River.

3.3 Long-term correlation characteristic of annual runoff process

The results of the wavelet analysis above tell us the annual runoff in the mainstream of the Tarim River present certain long-term trends at the time scale of 16 (2^4) years. As a whole during the period from 1957 to 2002, the annual runoff in the mainstream of the Tarim River basically had presented a decreasing trend. If the time extent from 1958 to 2005 is divided into three periods in accordance with the range of 16 (2^4) years, i.e. 1958–1973, 1974–1989 and 1990–2005, the trend of annual runoff in the mainstream of the Tarim River during each period can be clearly shown in Fig. 5, in which the solid line represents the time series of annual runoff, and the dotted line represents its linear trend.

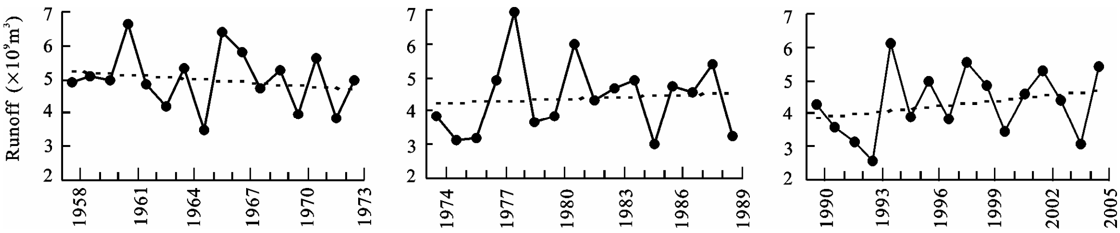

Fig. 5 Trends of annual runoff in different periods

Using R/S analysis method, the Hurst exponents for annual runoff in the mainstream of the Tarim River in different periods have been calculated.

The Hurst exponents in the three periods, 1958–1973, 1974–1989 and 1990–2005 are 0.5036, 0.6116 and 0.7150 respectively. In the first period (1958–1973), the Hurst exponent is 0.5036, equaling 0.5 approximately, which indicates that the annual runoff process was in chaos. In the second (1974–1989) and third (1990–2005) periods, the Hurst exponents are all greater than 0.5, which indicates that the annual runoff process showed a long-enduring characteristic. That is to say, in the two periods the next period will have the same trend with the preceding period. Figure 5 reveals that the annual runoff had decreased in the first period (1958–1973), and slightly increased in the second period (1974–1989) and third period (1990–2005). These trends correspond to the results indicated by the Hurst exponents. According to the Hurst exponent of the period from 1990 to 2005, we can affirm that the annual runoff in the mainstream of the Tarim River can be expected to increase slightly in the 16 years after 2005.

4 Conclusions

From the study on nonlinear characteristics of the annual runoff process in the mainstream of the Tarim River by using the wavelet analysis method and the fractal theory, we draw the following conclusions:

(1) The annual runoff process in the mainstream of the Tarim Rive is a complex nonlinear system, which has nonlinear trend, as well as fractal and chaotic characteristics.

(2) From a large time scale point of view, i.e. the time scale of 16 (2^4) years, the annual runoff in the mainstream of the Tarim River basically shows a slightly decreasing trend as a whole from 1958 to 2005. If the time scale is reduced to 8 (2^3) or 4 (2^2) years, the annual runoff still displays the basic trend as the larger time scale, but it has fluctuated more obviously during the period.

(3) The correlation dimension for the annual runoff process in the mainstream of the Tarim River is 3.4307, non-integral, which indicates that the process has both fractal and chaotic characteristics. The correlation dimension is above 3, which means that at least four independent variables are needed to describe the dynamics of the annual runoff process.

(4) The Hurst exponent for the first period (1958–1973) is 0.5036, equaling 0.5 approximately, which indicates that the annual runoff process is in chaos. The Hurst exponents for the second (1974–1989) and third

(1990–2005) periods are both greater than 0.5, which indicate that the annual runoff process showed a long-enduring characteristic in the two periods. According to the Hurst exponent for the period from 1990 to 2005, we can conclude that in the 16 years after 2005, the annual runoff in the mainstream of the Tarim River will show a slightly increasing trend.

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