Chin. Geogra. Sci. 2009 19(2) 158–167
DOI: 10.1007/s11769-009-0158-1
www.springerlink.com

Multiple Time Scale Analysis of River Runoff Using Wavelet Transform for Dagujia River Basin, Yantai, China

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Abstract: Based on monthly river runoff and meteorological data, a method of Morlet wavelet transform was used to analyze the multiple time scale characteristics of river runoff in the Dagujia River Basin, Yantai City, Shandong Province. The results showed that the total annual river runoff in the Dagujia River Basin decreased significantly from 1966 to 2004, and the rate of decrease was $48\times10^6 m^3/10yr$, which was higher than the mean value of most rivers in China. Multiple time scale characteristics existed, which accounted for different aspects of the changes in annual river runoff, and the major periods of the runoff time series were identified as about 28 years, 14 years and 4 years with decreasing levels of fluctuation. The river runoff evolution process was controlled by changes in precipitation to a certain extent, but it was also greatly influenced by human activities. Also, for different time periods and scales, the impacts of climate changes and human activities on annual river runoff evolution occurred at the same time. Changes in the annual river runoff were mainly associated with climate change before the 1980s and with human activities after 1981.
Keywords: multiple time scale; river runoff; climate change; Morlet wavelet transform; Dagujia River

1 Introduction

River runoff evolution process of a regional hydrological system can be influenced by both human activities and natural factors, including changes in climate, land use, vegetative cover, infiltration, evaporation, etc. So it includes not only the characteristics of tendency, periodicity and break, but also highly nonlinear, stochastic and multiple time scale attributes (Jury and Melice, 2000; Kantelhardt et al., 2003; Lettenmaier et al., 1994; Luo et al., 2002). It is not an easy task to comprehensively study river runoff evolution characteristics and its driving forces, although it can provide much important and fundamental information for land use and water resources management, the design of civil projects, etc. Fortunately, the analysis and simulation of river runoff variation has a long history. About 50 years ago, Hurst (1951) found that turbulent flows from various rivers took on "long-range statistical dependencies" characteristics. Subsequently, increasing numbers of researchers addressed the issue of identifying variations in river runoff characteristics of watersheds over the world and explored their relationships with climate change and human activities (Luo et al., 2002; Lettenmaier et al., 1994; Singh and Kumar, 1997). Such studies resulted in many great and beneficial achievements, but they mainly focused on the absolute values of the raw data and only considered a single time scale. Therefore it is very difficult to identify multiple time scale characteristics of the river runoff evolution process from such past studies. In the early 1980s, Morlet (1983) focused on geophysical seismic signals and introduced a wavelet analysis method that could provide the potential for analyzing the multiple time scales constituting, or contained within, non-stationary spatial or temporal signals. As an alternative to the Fourier transform in preserving

Received date: 2008-08-05; accepted date: 2009-02-20
Foundation item: Under the auspices of National Key Science and Technology Support Program of China (No. 2006BCA01A07-2), National Natural Science Foundation of China (No. 40101005), Science Foundation of Shandong Province, China (No. Q02E03)
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local, non-periodic, multiple time scale phenomena, wavelet analysis tools are currently widely used in diverse applied research fields related to image coding and compression (Antonini et al., 1992, Villasenor et al., 1995), signal processing and de-noising (Rioul and Vetterli, 1991), medical diagnosis (Akay, 1997), fractal analysis (Davis et al., 1994) and numerical approximation methods. In the field of hydrology and water resources science, one of the first wavelet transform studies was carried out by Kumar and Foufoula-Georgiou (1993). Meyers and Obrien (1994) performed another study in which the variability of ocean temperature was explained. More recently, wavelet analysis has been applied to examining the multiple time scale variations of river runoff in a region. For example, Smith et al. (1998) used a discrete wavelet transform to analyze daily discharge records from five different regions, and Saco and Kumar (2000) complemented their work. Labat et al. (2000) studied rainfall rates and river runoff amounts measured at the outlet of karstic springs located in the Pyrénées and on the Larzac Plateau, and clarified the temporal variability of the relationship between the two processes. Jury and Melice (2000) analyzed the rainfall records of Durban, South Africa, and the Nile River flow in southern Egypt from 1871 to 1999, and applied a wavelet transform to analyzing the records to determine the comparative strengths of intra-seasonal and up to decadal cycles. Xu et al. (2008) analyzed the long-term trend and fractal of the annual runoff process occurring in the mainstream of the Tarim River by using the wavelet analysis method and fractal theory. Most of those cited papers and other studies on the use of wavelet analysis have shown that the wavelet transform is an effective tool for precisely locating irregularly distributed, multiple time scale characteristics in time or space.

In this study, we chose the Dagujia River Basin in Yantai City, Shandong Province as a study area for the following reasons. Firstly, the Dagujia River Basin is located entirely within the hilly area of Jiaodong Peninsula, which enables it to be representative of hilly river basins similarly situated. Secondly, the strong anthropogenic pressure on the water resources in the basin has resulted in soil and water conservation in the Dagujia River Basin. Therefore, many hydrological projects have been founded since the 1980s, which have strongly impacted the spatio-temporal distribution of river runoff. Finally, the climate of the river basin had changed greatly during the last two decades of the study period and this has also influenced the river runoff evolution process (Liu et al., 2006; Liu et al., 2007).

Therefore, the main objective of this study was to identify the multiple time scale characteristics of the river runoff evolution process of the Dagujia River Basin through the use of the multi-resolution function of a wavelet transform. We also intended to explore the relationships between river runoff variation and changes in climate and human activities in order to provide basic data and a scientific basis for the reasonable exploitation, utilization and prediction of the regional water resources.

2 Data and Method

2.1 Study area

The Dagujia River is the principal water source of irrigation, municipal and industrial water for Yantai City, Shandong Province, China. The river basin, with an area of 2296km^2, is located approximately in 37°00′–37°40′ N and 120°50′–121°20′E. The basic features of the river courses in the Dagujia River Basin are shown in Table 1. Climatically, the river basin belongs to the semi-humid monsoon region, the mean annual temperature is about 12.3℃ and the mean annual precipitation is 679.2mm. About 76.6% of the total annual precipitation and 92.6% of the total annual river runoff (1966–2004) were generated during July to October. Influenced by climate change and human activities, especially in the last two decades of the study period, the spatial and temporal distribution of river runoff has become increasingly more non-uniform.

2.2 Data sources

Based on the locations and foundation times of hydrological stations, the monthly river runoff data sets from

Table 1 Basic features of river course in the Dagujia River Basin

Mainstream length (km)	Mean width of basin (km)	Mean slope of Mainstream (‰)	River density (km/km^2)	Bend coefficient of river course	Asymmetric coefficient	Shape index
75.0	16.1	1.17	0.07	1.58	–0.25	0.26

1966 to 2004 were collected at the Fushan Hydrological Station, which was founded in 1951 and is located downriver, 11km from the estuary, and monitors a basin area of about 970km^2. Therefore, the variation in river runoff measured at this station basically reflects changes in the river runoff of the entire Dagujia River Basin. The monthly precipitation and temperature data for the same period are the mean values calculated from data collected from six different meteorological stations, namely Fushan, Taocun, Tiekou, Qingquanbu, Laoshukang and Guxian stations.

2.3 Method

2.3.1 Selection of wavelet function

A wavelet transform is the representation of a function by wavelets, where the wavelets are scaled and translated copies (known as "daughter wavelets") of a finite-length or fast-decaying oscillating waveform (known as the "mother wavelet"). Wavelet transforms can provide information about both time and frequency simultaneously, and enable a separation to be made between features associated with different characteristic length scales, so they have some advantages over traditional Fourier transforms. At present there are a large number of wavelet transforms available for various applications. In this study, the Morlet wavelet, a complex non-orthogonal continuous wavelet, was selected to analyze the multiple time scales inherent in our data series. In choosing the Morlet transform, we mainly considered the following factors:

Firstly, it is difficult for orthogonal or discrete wavelets to identify the continuous multiple scales contributing to a signal. In contrast, when using a non-orthogonal wavelet transform, one can use an arbitrary set of scales to build up a more complete picture.

Secondly, a complex wavelet transform can provide both amplitude and phase simultaneously, and is better adapted for capturing oscillatory behaviors, but a real wavelet transform returns only a single component and can be used to isolate peaks or discontinuities.

Finally, the advantage of the Morlet wavelet over other options, such as the Mexican hat wavelet, lies in good definition in the spectral-space. When the non-dimensional frequency is greater than five, the Morlet wavelet scale is almost identical to the corresponding Fourier period of the complex exponential (Torrence and Compo, 1998; Torrence and Webster,1999; Farge, 1992; Meyers et al., 1993).

2.3.2 Morlet continuous wavelet transforms

The basis of a Morlet wavelet (ψ_0) consisting of a plane wave modulated by a Gaussian function can be defined as:

$$\psi_0(\eta) = \pi^{-1/4} e^{i\omega_0\eta} e^{-\eta^2/2} \tag{1}$$

where η is a nondimentional "time" parameter, ω_0 is the non-dimensional frequency (here taken to be 6 to satisfy the admissibility condition) (Farge, 1992; Torrence and Compo, 1998).

The continuous wavelet transform (CWT) of a discrete signal $x(t)$ with a Morlet wavelet (ψ_0) is described by the convolution of $x(t)$ with a set of dilated and translated wavelets:

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

where, a is the scale parameter, b is the translation parameter, the $*$ indicates the complex conjugate and $W_x(b, a)$ denotes the wavelet coefficient. Thus, the concept of frequency is replaced by that of scale. Using the program Suffer 8.0, the variation of $W_x(b, a)$ is depicted by two-dimensional isogram, in which b is denoted by the y-coordinate and a is represented by the x-coordinate. Thus, we can analyze and identify the river runoff variation characteristics at different time scales from the isograms.

The wavelet variance ($W_f(a)$) used to detect the main periods contributing to a signal can be expressed as:

$$W_f(a) = \frac{1}{a}\int_{-\infty}^{\infty} \left|W_x(b,a)\right|^2 \mathrm{d}b \tag{3}$$

Since the river runoff data sets used in this paper are of finite length and the Morlet wavelet is not completely localized in time, errors will occur at the beginning and end of the wavelet power spectrum. To reduce the edge effects we carried out a symmetry extension at both ends of the river runoff time series before undertaking the wavelet transform and then removed them.

3 Results and Analyses

3.1 Multiple time scale distribution of river runoff

3.1.1 Basic variation characteristics

As seen from Fig. 1, the river runoff in Dagujia River noticeably decreased from 1966 to 2004, and the rate of decrease was 48×10^6m^3/10yr, which was higher than that of the mean value of most rivers in China. Further analysis showed that the river runoff evolution process had passed through approximately four stages during the study period: mean flow period (1966–1970), high flow period (1971–1980), low flow period (1981–2000) and mean flow period (2001–2004). In addition, the river runoff variation coefficient in the Dagujia River was 0.841, higher than that of most rivers in China (Jiang et al., 2005), which indicated that the annual river runoff distribution in the Dagujia River Basin were very irregular during the study period.

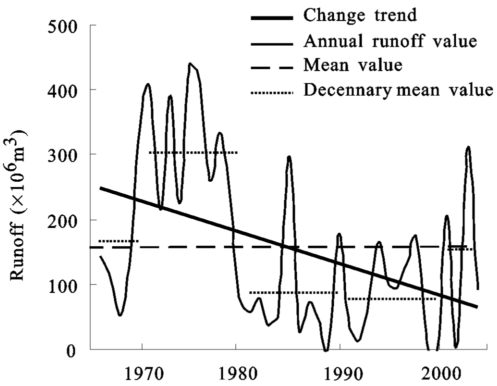


Fig. 1 Changes in annual runoff in the Dagujia River Basin in 1966–2004

3.1.2 Multiple time scale distribution of annual river runoff evolution

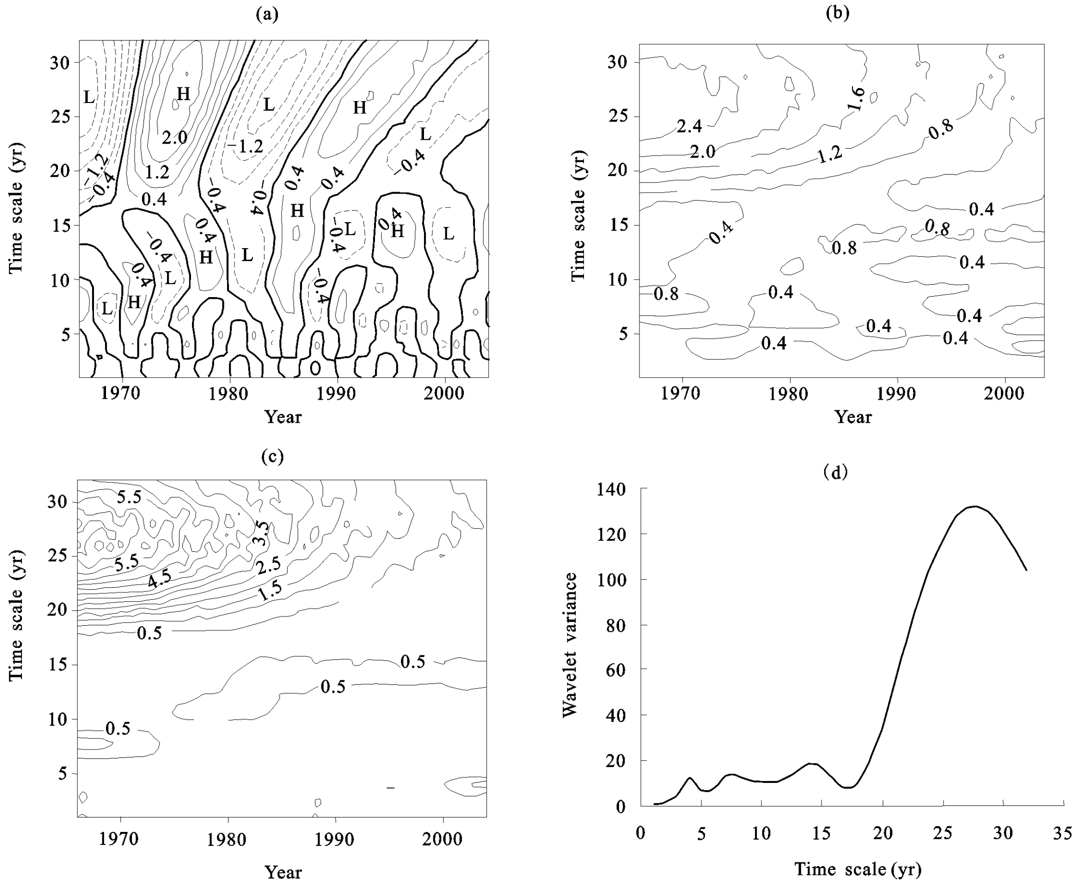
(1) Realpart. The realpart contours of the wavelet transform coefficients (Fig. 2a) clearly identify both the distribution conditions and the phase of the signal for different time scales (the signal refers to the annual river runoff time series for the Dagujia River measured in Fushan during the period 1966–2004).

Based on the realpart isogram of the Morlet wavelet transform coefficients, we can identify the multiple time scales that constitute the river runoff time series and we can estimate river runoff variation trends over different time scales. Figure 2a showed that the river runoff generated obvious quasi periodic oscillations (QPOs). Data revealed that the river runoff included three kinds of QPOs, namely 18–32 years, 8–17 years and 3–7 years. Seen from the perspective of the 18–32-year time scale, we found that river runoff changes occurred in two-time QPOs, and the detailed temporal distribution were, sequentially, a relatively low flow period before the 1970s, a relatively high flow period during the 1970s, a relatively low flow period from 1981 to 1989, a relatively high flow period from 1990 to 1996, and a relatively low flow period from 1997 to 2004. Those contours were still not closed in 2004, which indicated that the river runoff would still be in a relatively low flow period for an indefinite time at this time scale. At a time scale of 8–17 years, there were five QPOs where the high flow periods occurred in 1966–1967, 1970–1973, 1976–1980, 1984–1989 and 1993–1997 while the low flow periods occurred in 1968–1969, 1974–1975, 1981–1983, 1990–1992 and 1998–2003. Changes in the QPOs at the two time scales mentioned above had extraordinary stability in the entire study period. The QPOs at a time scale of 3–10 year basically occurred in the 1980s and later. For the smaller time scales, the variations between high and low flow periods changed more frequently and were often nested in a larger QPO. Hence the definitive time domain should be considered when necessary. Further study of the time scale of 8–17 years showed that the time scale of annual river runoff increased gradually from about 10 years to around 15 years, which indicated that the change trend of annual river runoff became to be stable.

(2) Module. In a period of time, the module values of a Morlet wavelet transform coefficients can depict the distribution of energy density in QPOs with different time scales. The larger the module values of the wavelet transform coefficients, the stronger the QPOs at corresponding time intervals or scales. In Fig. 2b, the module values were the largest for a time scale of 25–32 years, which indicates that the QPOs in this time scale changed most, the variations in QPOs for a time scale of 18–22 years were less, and the changes in QPOs for other time scales were the least.

(3) Module square. The module square of wavelet transform coefficients is equal to the wavelet energy spectrum, from which we can analyze the oscillation energy of a signal for different time scales. The contours of the module square in Fig. 2c show that the variation periods for the time scale of 25–32 years were most obvious and its energy was strongest, whereas the periodic change was typical and the strongest influence range of the oscillation energy was only distributed in the years before 1980. The energy at a time scale of 10–15 years was relatively weak but distributed more broadly and almost occupied the entire time period, i.e. from 1974 to 2004.

(4) Wavelet variance. The analysis of the contours of the realpart, module and module square can only indicate



In Fig. 2a, thin solid lines are positive values of wavelet coefficients and represents relatively high flow periods, "H" is the center of positive values; dashed lines are negative values and represents relatively low flow periods, "L" is the center of negative values; thick solid lines stand for "zero" values of wavelet coefficients

Fig. 2 Realpart (a), module (b), and module square(c) of Morlet wavelet transform coefficients and wavelet variance (d) of annual river runoff

the range of the periodic changes constituting the annual river runoff time series. Using wavelet variance, we can confirm some of the main periods that determined the change characteristics of river runoff during the entire study period and we can predict possible future variation trends. There are four peak values in Fig. 2d, which were located in the time scales of 4 years, 8 years, 14 years and 28 years. The largest peak value corresponds to the time scale of 28 years, illustrating that the 28-year period fluctuated most and it could be considered as the first main period. The time scales of 14 years, 8 years and 4 years corresponded to the second, third and the fourth periods, respectively. In short, the four periods mentioned above described the variation characteristics of annual river runoff during the entire study period.

Next we plotted the realpart values of the wavelet coefficients for the first and second periods separately in Fig. 3. The 14-year time scale in Fig. 3a demonstrates that the annual river runoff went through about four QPOs and that the mean oscillation period was about 9.5 years. Figure 3b shows that the annual river runoff underwent about two QPOs for the time scale of 28 years, and that the mean oscillation period was approximately 20 years. Since both the oscillation energy and the contribution to the variance of primitive river runoff time series were the greatest for the 28-year time scale, the low frequency wave would probably continue to develop for a further five years, i.e., the river runoff in the Dagujia River Basin will continue to be in a relatively low flow period until about 2010, and the river runoff will then revert to a relatively high flow period from 2010 to 2020.

3.2 Driving forces of multiple time scale distribution of river runoff evolution

The occurrence and evolution of river runoff are complex

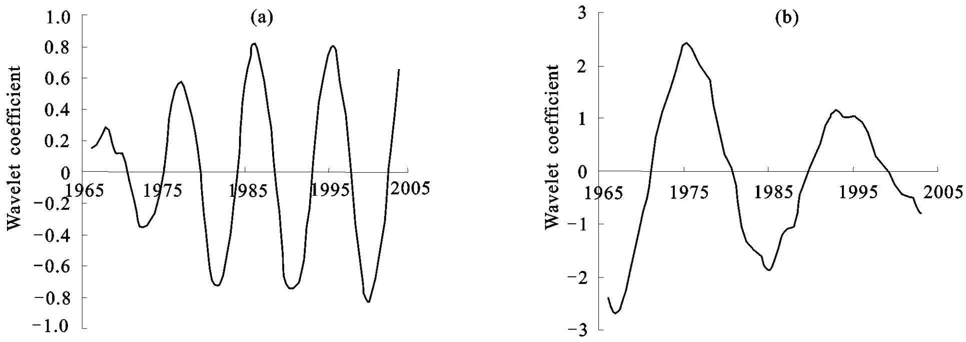


Fig. 3 Wavelet coefficients realpart at time scales of 14 years (a) and 28 years (b)

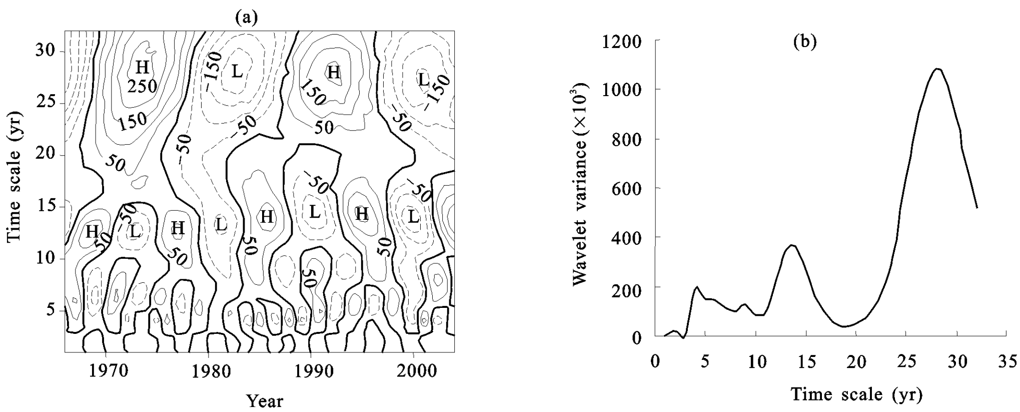
pocesses affected by many factors. In this paper, we concentrated on the impacts of climate change and human activities on river runoff in the Dagujia River Basin.

3.2.1 Impacts of climate change on river runoff

There exists a gray relationship between climate change and river runoff. Gray relational analysis was used to reveal the degree of the impacts of various climatic factors on river runoff. Defining X as the gray relational factor set, $X_0(t)\in X$ as the consulting sequence, $X_i(t)\in X$ (i=1, 2, …, n; $n\geq 2$, here, n=3), as the comparative sequence, where $X_0(t)$ and $X_i(t)$ are named factor sequences, considered separately. Here, $X_0(t)$ denotes the river runoff sequence and $X_i(t)$ represents the climatic factor sequences, where $X_1(t)$ is the mean annual precipitation, $X_2(t)$ is annual evaporation and $X_3(t)$ is mean annual temperature, respectively, and the relational coefficients of $X_0(t)$ and $X_i(t)$ are represented by r_i. Here, the whitening value of the gray derivative was taken to be 0.5 and the data were standardized to eliminate the dimensional influence. The relational coefficients between $X_0(t)$ and $X_i(t)$ were calculated: r_1=0.828, r_2=0.702, r_3=0.609, which identified precipitation as the main driving force of the river runoff evolution process among the climate factors considered.

In order to further study the impacts of precipitation on multiple time scale distribution of the river runoff evolution process, we analyzed the precipitation contemporaneously with the river runoff based on the Morlet wavelet transform approach (Fig. 4). Figure 4a indicates that the variation in precipitation was also described by multiple time scales of 22–32 years, 10–17 years and 3–10 years, and that the main periods of change were 28 years, followed by a 14-year period, and a 4-year period, which was the least variable (Fig. 4b), all of which were almost identical to the multiple time scales involved in the river runoff changes. This indicates that the changes in precipitation controlled the river runoff evolution process to a great extent.

However, Table 2 shows that the decadal range of changes in the annual river runoff was far bigger than



In Fig. 4a, thin solid lines are positive values of wavelet coefficients and represents relatively high flow periods, "H" is the center of positive values; dashed lines are negative values and represents relatively low flow periods, "L" is the center of negative values; thick solid lines stand for "zero" values of wavelet coefficients

Fig. 4 Realpart of wavelet transform coefficients (a) and wavelet variance (b) of annual precipitation that of the contemporaneous precipitation (except for the period of 1966–1970). Using the mean range of the changes during 1981–2004 as an example, when compared with the mean annual range of changes for the entire study period, the river runoff decreased by 39.49%, which was far higher than that of the contemporaneous mean annual precipitation that was reduced by 7.91%. The different correlation coefficients between precipitation and runoff for the various periods, and the corresponding significance levels, further indicate that the trends of their respective changes were dissimilar, which suggests that the river runoff evolution process is also influenced by other factors.

Table 2 Decadal range of changes in mean annual precipitation and river runoff in Dagujia River Basin

	P-annual (mm)	*R*-annual ($\times10^6$m^3)	Range of change (%)		Correlation coefficient
			P-annual	*R*-annual	
1966–1970	702.84	161	4.96	2.55	0.92*
1971–1980	780.11	303	16.5	92.99	0.98**
1981–1990	600.71	87	–10.29	–44.59	0.82*
1991–2004	592.75	79	–11.48	–49.68	0.93**
1966–1980	754.35	256	12.65	63.06	0.93**
1981–2004	616.70	95	–7.91	–39.49	0.88**

Notes: * Coefficients are significant at 0.01 level, and ** at 0.001 level

3.2.2 Impacts of human activities on river runoff

Analyzing cumulative river runoff for the study period can clearly reflect the impact of human activities on the river runoff evolution process (Fig. 5). The presence or lack of deviation from the system is the main basis for judging the degree of the impact of human activities on the river runoff evolution process. A deviation, which occurred from 1980 onwards, can be clearly seen in Fig. 5. Before 1980, the cumulative river runoff data points were generally linearly distributed with some minor fluctuations, which indicates that the impact of human activities was not significant during this period. Relative to the river runoff accumulation before 1980, the distribution of the data points represented an obvious system deviation in 1981–2004, which suggests that human activities had exerted much greater impacts on the river runoff evolution process. This was mainly attributable to several water resources crises that had occurred in the Yantai City since 1980, and in order to alleviate these conditions some measures were taken, such as increasing the reservoir capacity, intercepting and saving river runoff, etc. Government statistics show that the water conservancy department had established many hydrological projects in the river basin in 1980–2002, which notably included one large-scale reservoir, one middle-scale reservoir, one groundwater reservoir and six barrages, and that the capacity for intercepting and saving surface water and using groundwater increased to 280×10^{6}m^3 and 202×10^{6}m^3, respectively. Therefore, when compared with the mean annual river runoff of 542×10^{6}m^3 occurring in 1959–1980, mean annual river runoff was reduced to 175×10^{6}m^3 during the period 1980–2002. Other important factors included population growth and increases in industrial, agricultural and domestic water consumption (Table 3). Moreover, the soil and water conservation measures also played an important role in the river runoff evolution process by changing the underlying surface conditions of the river basin. The decrease of areas losing water and undergoing soil erosion was around 67×10^{3}ha while vegetation coverage improved by about 15%–20% during 1980–2002, all of which led to reduction in river runoff amounts.

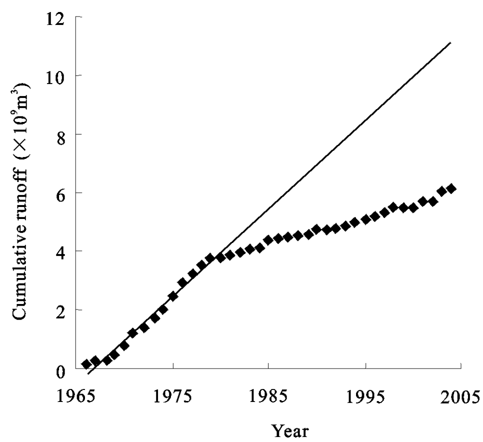


Fig. 5 Cumulative river runoff as a function of time in Fushan Hydrological Observation Station

Table 3 Comparison of population, irrigated area, and water consumption in Yantai City in 1980 and 2002

Year	Population ($\times10^6$)	Irrigated area ($\times10^3$ha)	Irrigated water usage* ($\times10^9$m^3)	Industrial water use** ($\times10^6$m^3)	Domestic water use ($\times10^6$m^3)
1980	5.672	323	2.321	85	172
2002	6.467	346	2.486	1518	323

Notes: * Irrigated water usage is calculated from (irrigated area × irrigated water used per hectare). ** Industrial water use is the product of total industrial production value (the price at corresponding year) and water consumption per ten thousand yuan, which was 267m^3 in 1980 and 80m^3 in 2002

In order to further identify the impact of human activities on the river runoff evolution process in the Dagujia River Basin, we adopted a subentry reduction method based on a simple water balance principle, combined with the basin characteristics, to calculate natural river runoff, and the water resources development and utilization ratio (W) defined as: $W= (R_n–R_0)/R_n\times100\%$, where, R_n is the natural river runoff and R_0 is the observed river runoff. Given the physical and practical conditions of the river basin region, the factors responsible for the reduction of flow in water courses were mainly the increased allocation of water for irrigation, industry, and domestic uses, and the variation of water levels in large-scale reservoirs (Table 4).

A well-managed level of water resources development and utilization requires that the water resources development and utilization ratio does not normally exceed 30% and takes 40% as the extreme upper limit. Table 4 showed that the ratio for the river basin generally increased with time. In the period 1966–1980, the average ratio was 28.47%, indicating that the period was a well-managed development and utilization stage. However, after 1980, the mean ratio was 39.95%, and greater than 60% in some years. In the most extreme cases, the ratios were even 100% in both 1999 and 2000, which led to the sharp reduction in river runoff, resulting in a series of ecological and environmental problems.

The wavelet transform analysis (Table 4) showed that the changes in the impact of human activities on river runoff were also described in terms of multiple time scales, whereby the 27-year period was the first main period, 11-years was the second and 5-year was the third, which were almost identical to the multiple time scales identified in association with the variations in river runoff.

4 Conclusions

In this study, we conducted a detailed analysis of multiple time scale characteristics involved in the river runoff evolution processes and their driving forces in the Dagujia River Basin by using a Morlet wave transform and other mathematical methods, such as a grey relational an-

Table 4 Observed river runoff (R_0), natural river runoff (R_n), and water use ratio (W) in Dagujia River Basin

Year	R_0 ($\times10^6$m^3)	R_n ($\times10^6$m^3)	W (%)	Year	R_0 ($\times10^6$m^3)	R_n ($\times10^6$m^3)	W (%)	Year	R_0 ($\times10^6$m^3)	R_n ($\times10^6$m^3)	W (%)
1966	143.8	187.3	23.22	1980	80.7	122.4	34.07	1994	165.8	246.8	32.82
1967	115.1	134.5	14.42	1981	57.3	100.9	43.21	1995	102.5	158.2	35.21
1968	53.6	83.4	35.73	1982	77.4	102.4	24.41	1996	95.5	171.1	44.18
1969	147.0	200.6	26.72	1983	36.7	60.9	39.74	1997	134.1	183.1	26.76
1970	347.6	393.3	11.62	1984	56.2	105.3	46.63	1998	170.9	203.6	16.06
1971	406.8	528.9	23.09	1985	304.0	503.8	39.66	1999	0.0	2.0	100.00
1972	214.7	276.3	22.29	1986	30.4	49.2	38.21	2000	0.0	4.0	100.00
1973	393.1	564.1	30.31	1987	72.8	162.0	55.06	2001	210.4	324.6	35.18
1974	223.5	341.2	34.50	1988	49.2	90.7	45.76	2002	0.9	1.7	47.06
1975	437.4	653.2	33.04	1989	7.0	18.0	61.11	2003	317.7	496.5	36.01
1976	421.9	545.0	22.59	1990	180.6	452.8	60.11	2004	92.1	201.2	54.22
1977	259.0	402.6	35.67	1991	44.9	50.5	11.09	1966–1980	255.5	357.2	28.47
1978	335.0	547.3	38.79	1992	12.0	17.5	31.43	1981–2004	95.0	158.2	39.95
1979	254.0	377.5	32.72	1993	62.7	89.2	29.71				

alysis. The following conclusions can be drawn from this paper:

(1) The annual river runoff in the Dagujia River Basin followed a significant decreasing trend and exhibited visible evolution processes between high and low flow periods during the study period (1966–2004). Seen from the absolute values of the data set for river runoff, the period before 1980 belonged to a relatively high flow period and the period of 1980–2004 was a relatively low flow period. The pattern of the runoff changes during the first main period obtained from a wavelet variance indicated that the river runoff will still be in a relatively low flow period in the subsequent five years, and will then revert to a relatively high flow period from about 2010 to 2020.

(2) The evolution process of river runoff had significant multiple time scale characteristics of 18–32 years, 8–17 years and 3–7 years, and these time scales had different oscillation energy densities. The smaller time scales were often nested in a larger QPO and the evolution characteristics of river runoff were often different for the various time scales. Hence the study of river runoff evolution processes in a river basin must be made at established time scales. Therefore, the analysis of long time series and finer temporal scales (daily or even hourly) of river runoff should be the subject of future papers.

(3) The relationship between various climatic factors and river runoff was closest for precipitation, which indicated that changes in precipitation controlled the river runoff evolution process to a certain extent. However, the trends in their variation were somewhat dissimilar, which implied that the river runoff evolution process was also affected by other factors. The mean ratio of water resources development and utilization was 39.95% (40% is the extreme upper limit of a well-managed system) after 1980, which demonstrated that human activities had a great and detrimental impact on river runoff evolution.

(4) The impacts of both climate change and human activities on the river runoff evolution process existed simultaneously in different time scales. The large and small time scales of climatic change influenced the long-term and short-term variations of river runoff, respectively. Similarly, human activities also influenced the spatial and temporal distribution of river runoff through hydrological projects, soil and water conservation measures, and changes in various water consumption needs.

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