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Multi-Time Scale Analysis of Runoff at the Yangtze Estuary Based on the Morlet Wavelet Transform Method

KUANG Cui-ping[1], **SU Ping**[1], **GU Jie**[2*], **CHEN Wu-jun**[3], **ZHANG Jian-le**[3], **ZHANG Wan-lei**[3], **ZHANG Yong-feng**[3]

1 Department of Hydraulic Engineering, College of Civil Engineering, Tongji University, Shanghai 200092, China

2 College of Marine Sciences, Shanghai Ocean University, Shanghai 201306, China

3 Marine Environmental Monitoring Center of Hebei Province, Qinhuangdao 066002, China

**Corresponding author, e-mail: jgu@shou.edu.cn; First author, e-mail: cpkuang@tongji.edu.cn*

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Abstract: Runoff series of the Yangtze River presents an intricate variation tendency under the reinforced influence of human activities. The Morlet Wavelet Transform method has been applied to analyze the annual runoff data from 1950 to 2011 at the Yangtze River Estuary. It can clearly reveal the multi-time scales structure, break point, change and distribution of periodic variation in the different time scales of the runoff series. The main conclusions are that: 1) Repeated periodic oscillations accompanied by an extremely large fluctuation are presented in the runoff series with an obvious difference between wet and dry years, and the major periods of the time series are about 3, 8, 16 and 23 years respectively. Among them, the presented maximum periodic oscillation is 23 years scale. 2) In the 23-year time scale, the wet periods are 1950-1958, 1969-1980 and 1992-2003, and the dry periods are 1959-1968, 1981-1991 and 2004-2011. 3) It can be predicted from the view of long time scales that the low annual runoff will likely occur in the near future.

Keywords: Datong station; Wavelet transform; Runoff series; Periodic characteristics

Introduction

Runoff takes an important role in linking the circulation of material between terrestrial and marine ecosystems, and controlling the development and evolution of estuaries and deltas. Over the years, with the rapid economic development and population growth, human activities played a much more important role in the hydrological cycle (Mupenzi et al. 2011; Ding et al. 2011). Notable changes in flow discharge emerged in a number of rivers, for instance, the Nile, Parana, Mississippi and Yellow River (Fanos 1995; Milliman et al. 2008; Huntington 2005; Wang 2006). The Yangtze River Delta region is among the most economically developed and densely populated areas in China. In the past two decades, some major hydraulic engineering projects like the completion of the Three Gorges Reservoir in the upper reach of the Yangtze River, the South-to-North Water Diversion Project and the channel regulation of the Yangtze estuary have produced huge changes to the hydrological environment (Fang et al. 2011). Especially since the Three Gorges Dam, which is the world's largest dam, started operation in 2003, the runoff of the Yangtze River estuary decreased by 10% during the 2004 to 2011 period compared with the annual mean value from 1950 to 2003.

Consequently, research on the hydrological characteristics of the delta is of great importance in many fields like management of water resource

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reserves. This is particularly true with the increasing demands for water, erosion and remodeling of the delta and coastal zone, and the channel regulation and construction of the Yangtze estuary. Analyzing runoff records can give significant ideas for both past and future characteristics of runoff, especially the river runoff measured at the estuary which reflects the changes to the entire basin. For this purpose, engineers and scientists have conducted a series of research on the variation and characteristics of runoff series at the Yangtze estuary (Wang et al. 2006; Zhang et al. 2006; Zou et al. 2007; Wang et al. 2009; Zhu et al. 2012). Since the runoff series is a highly complicated hydrological process influenced by several factors, the conventional methods present difficulties in analyzing the changing process, so some new techniques have been produced and quickly expanded.

Wavelet Transform analysis, first proposed in 1980s and then developed rapidly during the last three decades, is a time-frequency analytical approach to evaluate the time scales of signals, and it has the remarkable characteristic of multi-resolution analysis. The traditional signal analysis is based on the Fourier transform, which is generally fully unfolded in the frequency domain, and contains little information about the time domain (Chui 1992). In this situation, the Fourier analysis is usually applied in frequency analysis of stationary time series. Wavelet Transform analysis has the capacity of signal representation both in time and frequency domains. It is a better method than the Fourier transform for the study of the non-stationary time series, like hydrological processes affected by a variety of complex factors (Bing et al. 2012). Wavelet analysis can reveal the movement of the instantaneous frequency structure of a time series in detail with high accuracy and provide a new insight into the periodicity of hydrological time series. It can describe the processes such as long-term trends, periodic fluctuations and detect the singularity of runoff changes (Wang et al. 2002). Therefore, the wavelet analysis method is known as a mathematical “microscope” and widely applied in signal analysis of different fields of study. Many researchers have applied this method to analyze the variations of hydrologic time series (Kucuk et al. 2006; Wang et al. 2007; Xu et al. 2009; Li et al. 2014).

In this study, we will conduct a fundamental analysis based on the annual runoff series data at Datong hydrologic station in the Yangtze River from 1950 to 2011. Then the Morlet wavelet transform method will be applied to analyze the multi-time scales characteristics of the flow discharge time series. In order to reveal the periodicity of hydrologic annual time series, the data need to be pre-processed before the wavelet analysis is applied. The original runoff series data will be anomaly treated as the calculating data in wavelet transformation. The difference between the runoff value and the average will be used instead of the original series data as the calculating data in wavelet transformation.

1 Study Area

The Yangtze River, the third largest river in the world and the longest river (6380 km) in Asia, lies between 91°E and 122°E and 25°N and 35°N in China. It originates in the Tanggula Maintains in the Tibetan Plateau at about 6099 m above sea level and flows into the East China Sea via the Yangtze River Estuary. The river flows through 11 provinces and covers a drainage area of 1.8×10^6 km^2 (shown in Figure 1). Mean annual precipitation across the basin is approximately 1090 mm, but there is a high degree of spatial and temporal variation (Zhang et al. 2005). The Datong station is the final key controller in the lower reach of the Yangtze River and tidal limit of the Yangtze estuary. It is located 620 km from the estuary, and monitors the basin area of about 1.7×10^6 km^2, almost 95% of the whole Yangtze River Basin (Ying et al. 2005). Therefore, the variation in river runoff measured at this station reflects the changes in the river runoff of the entire Yangtze River Basin and the amount of fresh water flowing into the estuary region (Zhang et al. 2006; Dai 2010).

2 Method

Wavelet analysis is used for signal processing. Unlike the Fourier transform, the use of Wavelet analysis is relatively new and is a more powerful signal-processing tool. Wavelet analysis can

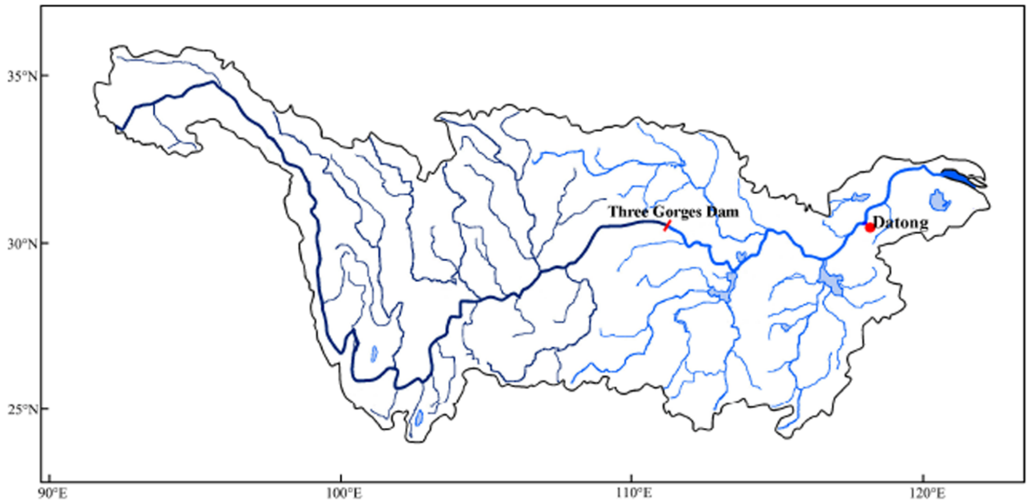

Figure 1 Sketch map of Yangtze drainage basin.

perform an analysis on the same non-stationary signal and chaotic processes, which could not have been processed appropriately using a Fourier transform. This type of analysis provides the user with further information on a localized section of the time-series. In addition, because the Wavelet analysis handles chaotic (i.e., noisy) data well, process-level information such as long-term trend, periodic fluctuations and the singularity of runoff changes under the effect of climate changes can be presented in this analysis.

For the wavelet function $\psi(t) \in L^2(R)$ (Percival et al. 2000), the continuous wavelet format is defined as:

$$\psi_{a,b}(t) = |a|^{-\frac{1}{2}} \psi(\frac{t-b}{a}) \tag{1}$$

The continuous wavelet transform of the signal (function) $x(t)$ is:

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

where $W_f(a,b)$ is the wavelet transform coefficient; $\psi(t)$ is the mother wavelet, $\psi(t)^*$ is the conjugate operator; a is the scale parameter and b is the translation parameter. Note, a is greater than zero. The wavelet transform can realize the characteristics of the function $x(t)$ both in time and frequency domains (Burrus et al. 1998). When the scale parameter a is smaller, the resolution of the frequency domain is lower, and the resolution of the time domain is higher; when a is bigger, the variations in resolution of the frequency and time domains become higher and lower, respectively.

In practical application, the hydrological time series are generally discrete. For the discrete series $x(k\Delta t)$, (k=1,2,...,N), where Δt is the sample time interval (Wang et al. 2002), the formula (2) can be rewritten as follows:

$$W_f(a,b) = |a|^{-\frac{1}{2}} \Delta t \sum_{k=1}^{N} x(k\Delta t) \psi^*(\frac{k\Delta t - b}{a}) \tag{3}$$

There are a number of different forms of the wavelet function $\psi(t)$, and the most common wavelet functions include Marr wavelet, Wave wavelet, Meyer wavelet, Haar wavelet and Morlet wavelet. Compared to the other wavelet forms, the Morlet wavelet is a locally periodic wave train, which can be obtained by taking a complex sine wave, and by localizing it within a Gaussian envelope. The wavelet transform has a real and an imaginary part, and the norm is the magnitude of this transform, which is related to local energy. Related research indicates that the Morlet wavelet is applicable in hydrological time series analysis (Wang et al. 2002, Zhang et al. 2004, Liu et al. 2009). We also choose the Morlet wavelet as the mother wavelet function in this study due to the fact that the Morlet wavelet well characterizes the local properties of both the time domain and frequency domain. The standard Morlet wavelet was defined as:

$$\psi(t) = e^{-\frac{t^2}{2}} e^{j\omega_0 t} \tag{4}$$

The real part and imaginary part of the Morlet plural wavelet function can be treated as two wavelet functions respectively. The wavelet with a plural function form has more advantages than the wavelet with a real function form in practical application. The phase difference between the real part and imaginary part is π/2, it can effectively reduce the oscillation of the coefficient modulus from real-valued wavelet transform and the generated errors on the analysis results. Meanwhile, separating the modulus and phase of wavelet transform coefficients can reflect the information about change of the phase and amplitude of hydrological time series. The real part of the wavelet coefficient can describe the characteristics of the signals both in different time scales and in different phases (Tian et al. 2007).

The wavelet variance $W_f(a)$ can be calculated as follows:

$$W_f(a)=\int_{-\infty}^{\infty}\left|W_f(a,b)\right|^2\mathrm{d}b \tag{5}$$

where $W_f(a,b)$ is the wavelet transform coefficient.

The wavelet variance is a reflection that reveal the distribution of signal fluctuations energy with the changing of scale a. The main periodicities that exist in the time series can be determined by the wavelet variance. Therefore, the scale or periodicity that plays the main role in a time series can be found very conveniently.

3 Results and Discussion

3.1 Basic variation characteristics

The runoff series at Datong station presented a fluctuating interannual variation from 1950-2011 as the changing process of annual runoff anomaly shown in Figure 2. The trend lines (dotted lines in Figure 2) for each decade concretely reflected this changing characteristic. The runoff in the 1960s and 1990s presented rising trend, while a decreasing trend appeared in the other decades. Though it exhibited rapid changes on the whole, there was no clear trend existing in the runoff series. The basic eigenvalues of the runoff statistic data including average, maximum and minimum values are shown in Table 1. From the cumulative anomaly of different decades in Table 2, we can conclude that there were repeated fluctuations appearing in the runoff time series. The runoff was high in the 1950s, and remained in a lower level from 1960s to 1970s. The runoff was in a relative balance during the 1980s. It was in the wetter time during the 1990s, and a reduced variation appeared after 2003. As a whole, the runoff in the early 21th century reduced rapidly compared with the 1990s.

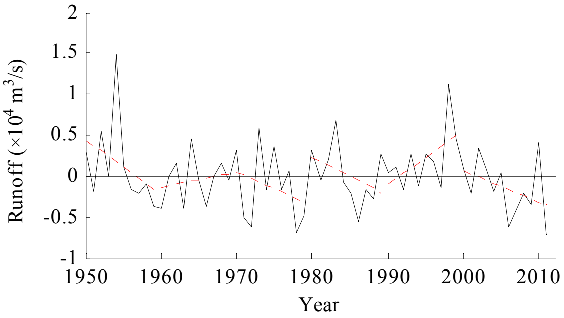

Figure 2 Annual runoff anomaly curve at Datong station from 1950 to 2011.

Table 1 Basic eigenvalues of annual runoff series from 1950-2011 at Datong station

Average (m^3/s)	Maximum		Minimum	
	Year	Value(m^3/s)	Year	Value (m^3/s)
28300	1954	43,100	2011	21,150

Figure 3 shows the monthly runoff variations and distributions at Datong station. Figure 3(a) reflects the change of monthly runoff values, and the percentages of each month are shown in Figure 3(b). The mean monthly distribution curve reveals that the runoff in flood season (from June to September) composed most of the annual runoff. These four months accounted for 51% of the total runoff, while that in dry season (from December to March) accounted for only a small portion of 15.7%. The percentage of runoff in flood season during 1954 and 2011 were 56.5% and 49.1%, respectively. Though obvious differences existing in the monthly runoff values of three series (see Figure 3(a)), the percentages shown in Figure 3(b) were quite close.

3.2 Periodic features and variation trend

The real part of Morlet wavelet transform coefficients has a significant variable, it shows the distribution and phase of periodic variation on different time scales. The wavelet coefficient does not represent the real runoff value but rather that a positive correlation exists between them. A positive wavelet coefficient value corresponds to the wet year of runoff time series and negative value

Table 2 The cumulative anomaly of annual runoff series at Datong station

Period	1950-1959	1960-1969	1970-1979	1980-1989	1990-1999	2000-2011
Cumulative anomaly (×10⁴ m³/s)	1.39	-0.51	-1.32	0.15	1.99	-1.71

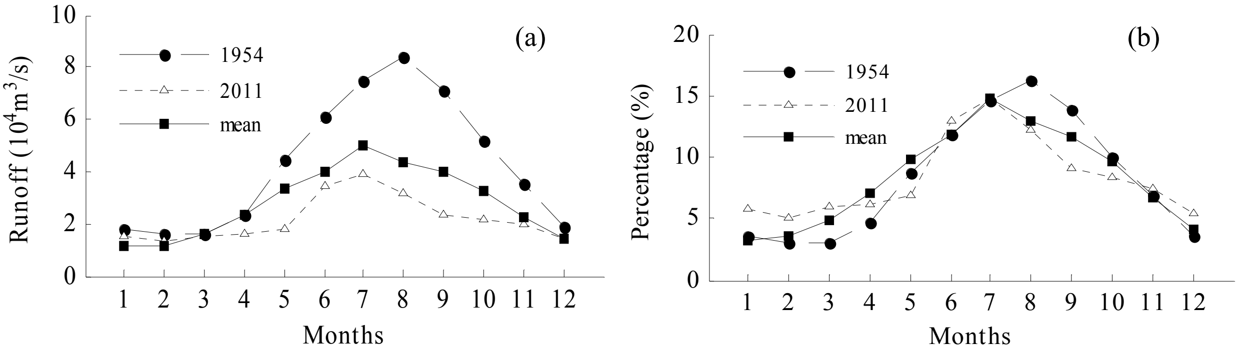

Figure 3 Monthly runoff distribution curve at Datong station.

correspond to the dry year. A value of zero indicates an average year. The intensive degree of the isoline reflects the strength of fluctuation. For this reason, the wavelet's real part can show the peak and valley structure of the runoff on different time scales.

The real part of Morlet wavelet transformation of runoff series at Datong station is shown in Figure 4. It indicates that the phase structure of the runoff series changes on different time scales and presents alternatively positive and negative variations over time. Complicated variations on a small scale nested in the large scale, and there are interannual and interdecadal variations existing in the runoff at Datong station. The X-coordinate represents time and the Y-coordinate represents scale. Figure 4 obviously shows the areas of positive and negative values of the real part of the wavelet transform, which reflect the alternatively wet and dry periods. It suggests that there are quasi-periodic variations on the time scales of 1-5 years, 6-12 years, 12-20 years and above 20 years in the annual runoff series. The corresponding center time scales are about 3, 8, 16 and 23 years. Judging from the entire study time, variation on the time scales of 12-20 years and 20 years above present periodic characteristics. The periodicities of 1-5 and 6-12 years time scales have a temporally local character, which is obvious in some periods and not so obvious in other periods. The variations on these time scales clearly reveal the multi-time scale structure, break point, change and distribution of periodic variation.

To confirm the main periods that determine the change characteristics of annual runoff at the Datong station, the variance of the wavelet transform coefficient is calculated as Figure 5 shows. It can be seen that there are four peak values which are located in the time scales of 3, 8, 16 and 23 years. In other words, the runoff time series have four periodic oscillations of 3, 8, 16 and

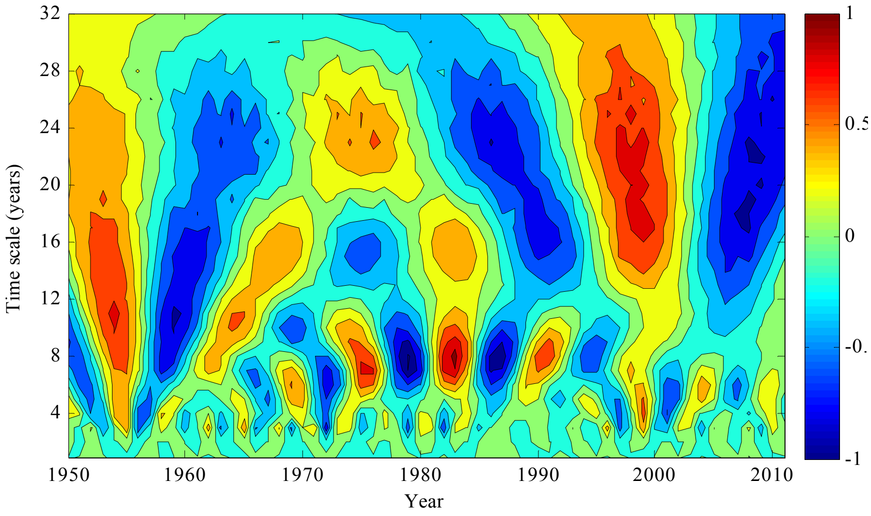

Figure 4 Time-frequency distribution of real-part of annual runoff at Datong station based on Morlet wavelet transform.

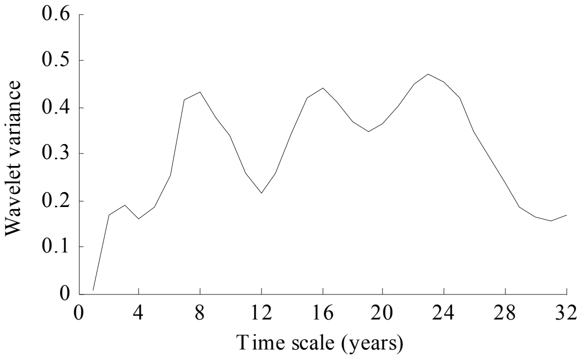

Figure 5 Wavelet variance diagram of annual runoff time series at Datong station.

23 years. The largest peak value corresponds to the time scale of 23 years, demonstrating that the 23 years period fluctuated most and it is considered as the first main period. The peak values of 16 and 8 years periods are quite close to the 23 year peak, and they are considered the second and third main periods respectively. The fourth main period is the 3 year period which fluctuates much more weakly than the others. The main periods of the runoff series are consistent with the period centers of the fluctuation shown in Figure 4 on the whole.

In order to reveal the fluctuation characteristic of the runoff time series more clearly, the variation processes over time of the wavelet coefficient corresponded to the three most obvious time-scales (8, 16 and 23 years) have been given out respectively in Figure 6. We can recognize the evolution process and mutation features of runoff on multi-time scales by analyzing the real-part changes of Morlet wavelet transform coefficient.

The variation process of the wavelet transform coefficient on an 8 year time scale is shown in Figure 6(a). Judging from the positive and negative values, the wet years are 1953-1956, 1961-1964, 1968-1969, 1974-1977, 1981-1984, 1989-1992, 1997-2000, 2004-2005 and 2009-2011. The dry years are 1950-1952, 1957-1960, 1965-1967, 1970-1973, 1978-1980, 1985-1988, 1993-1996, 2000-2003 and 2006-2008. The range trend of the process curve shows that fluctuations on an 8 year time scale have become weak since 2003 due to the impoundment of Three Gorges Reservoir, which obviously affected the interannual variations of runoff in the early phase of its operation. The value has already approached its normal value of accumulated years and decreased over time.

The variation process of the wavelet transform coefficient on a 16 year time scale is shown in Figure 6(b). According to the positive and negative value, the wet years are 1950-1956, 1965-1971, 1980-1986 and 1995-2003, the dry years are 1957-1964, 1972-1979, 1987-1994 and 2004-2011. 1957, 1965, 1972, 1980, 1987, 1995 and 2004 are the turning points of wet and dry years. The wavelet coefficients variation of 16 years time scale is quite steady during the whole study phase. The runoff time series had been in the late dry season since 2004, and it appears to reach the normal value and turn into the wet season possibly in the future years.

Figure 6(c) shows that fluctuations have emerged in the wavelet coefficients variation process of the 23 year time scale. By analyzing the changes in the real part of the transformation function in Figure 6(c), the wet years are 1950-1958, 1969-1980 and 1992-2003, the dry years are 1959-1968, 1981-1991 and 2004-2011. The key points of change process are 1959, 1969, 1981, 1992 and 2004. The variation of a 23 year time scale shows that the runoff time series was in the peak dry season from 2004 on the 16 year time scale, and it seems to be in the dry season for several years though a rising trend has already appeared.

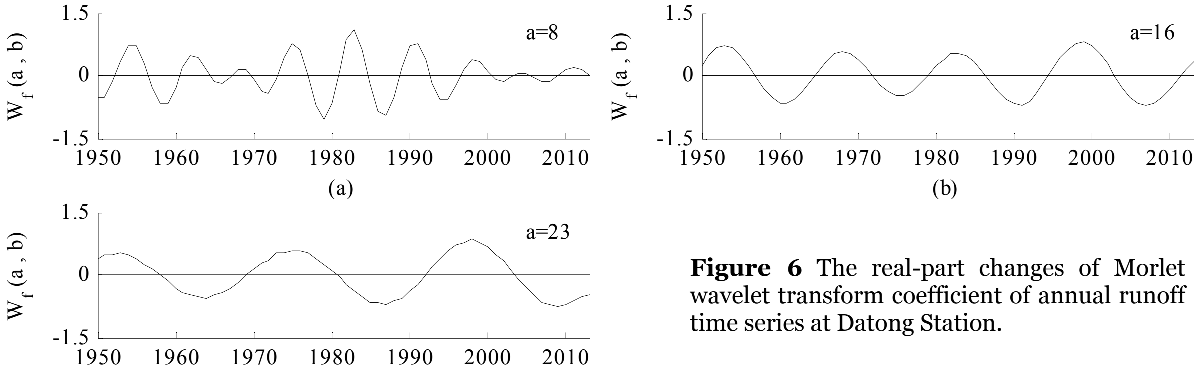

Figure 6 The real-part changes of Morlet wavelet transform coefficient of annual runoff time series at Datong Station.

The comparison of inflection points on interdecadal variations (16 and 23 year time scales) is shown in the Table 3. Even though these two time scales presented different changing processes, the decreasing trend both appeared since 2004 after the operation of the Three Gorges Reservoir.

Table 3 The comparison of inflection points on 16 and 23 years time scales

	16 year	23 year
Wet to dry years	1957, 1972, 1987, 2004	1959, 1981, 2004
Dry to wet years	1965, 1980, 1995	1969, 1992

The variations of different time scales reveal distinct periodic oscillations that appeared in the runoff series. Figure 6(a) reveals about eight periods of variation during the whole study phase and the last two periods weaken obviously. It can be concluded that the influence on the runoff series of the 8 year time scale had been immensely attenuated in the past 15 years. Figure 6(b) reveals that there are nearly four periods in the 16 year time scale, the amplitude of variation is quite stable during the whole study phase. Two completed periods are shown in the Figure 6(c), the gradually enhanced amplitude demonstrates the degree of influence on the runoff is increasing. In conclusion, the influence of the 8 year time scale on the runoff series presented a weakening trend since the 1990s, meanwhile the influence of the 16 and 23 years time scales has become dominant in recent years.

4 Conclusions

The Morlet Wavelet Transform method has been applied in this study to analyze the annual runoff time series from 1950 to 2011 at the Datong Station in the Yangtze River. This method has a significant capability to analyze the long-term time-series runoff, and can clearly reveal multi-time scales structures, breaking points, and change and distribution of periodic variation in the different time scales of the runoff series. The main conclusions are that:

Repeated periodic oscillations accompanied by an extremely large fluctuation are presented in the runoff series with an obvious wet and dry year change. There are quasi-periodic variations on the time scales of 1-5 years, 6-12 years, 12-20 years and 20 years above, and the corresponding major periods are about 3, 8, 16 and 23 years respectively. Among them, the presented maximum periodic oscillation is the 23 year scale, and it turned out to be the primary main period that determined the change characteristics of annual runoff. The 8 and 16 year scales also present intense periodic variation.

The variant process of the runoff series shows that there are several periods emerging in different time scales. In the entire study period, there are roughly 2, 4 and 8 periods corresponding to the 23, 16 and 8 year time scales respectively. The fluctuations of 16 and 23 year scales are quite smooth and the 8 year scale's fluctuation has weakened visibly since the 1990s. It indicates that the 16 and 23 year scales have played a dominant role in the recent years.

In the 23 year time scale, the higher runoff periods are 1950-1958, 1969-1980 and 1992 -2003, while the lower runoff periods are 1959-1968, 1981-1991 and 2004-2011. Accordingly, the break points are 1959, 1969, 1981, 1992 and 2004 respectively. In the 16 year time scale, the wet years are 1950-1956, 1965-1971, 1980-1986 and 1995-2003, the dry years are 1957-1964, 1972-1979, 1987-1994 and 2004-2011. 1957, 1965, 1972, 1980, 1987, 1995 and 2004 are the turning points of wet and dry years.

It can be predicted from the view of longer time scales that the lower annual runoff will likely occur in the near future; meanwhile a rising trend has already begun to appear.

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