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Periodical characteristics of baseflow in the source region of the Yangtze River

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Abstract: Baseflow, which represents the drainage of groundwater aquifers, is an essential component of runoff in hydrological basins. In the source region of the Yangtze River, the change of baseflow typically reflects the interactions between groundwater system and climatic factors in cold and arid areas. With modified Kalinen separation method, annual baseflow between 1957 and 2009 in this region was estimated and calculated. In comparison with the inner-annual variations of total streamflow, baseflow showed a weaker fluctuation. Before the 1980s, it was in a steady state; and after then, it demonstrated dramatic variations and large amplitudes. Based on the calculation results of baseflow, the real Morlet wavelet method was applied to reveal the periodical characteristics of baseflow as well as the precipitation and air temperature in the study area. It was found that annual baseflow has a 43-year trend as well as a 21-year period and a 7-year period. The 21-year period is most significant, with its wavelet coefficient having the largest fluctuation and amplitude. Summation of wavelet coefficients on these periods exhibits a similar change pattern with respect to that of annual baseflow. The summation curve takes a “W” shape, which means that the baseflow follows a four-stage sequence of descending–ascending–descending–ascending. As analyzed, the relationship among baseflow, precipitation and temperature is implied in the correlation between their normalized wavelet coefficients at different temporal scales. By the significant positive linear correlations both between precipitation and baseflow (correlation coefficient is 0.98) and between temperature and baseflow (correlation coefficient is 0.90) for the 43-year wavelet coefficients, it is suggested that the long-term increasing trends of precipitation and air temperature will lead to an increasing trend of baseflow. For wavelet coefficients of 21-year and 7-year periods, the positive linear correlation between precipitation and baseflow is significant. However, the correlation between air temperature and baseflow is not so evident, especially for the 21-year period. As a conclusion, correlation analysis with normalized wavelet coefficients showed that the change of annual baseflow was contributed mostly by the change of precipitation and secondly by the change of temperature.

Keywords: baseflow; climate; Kalinen separation method; Morlet wavelet; Yangtze River

The source region of the Yangtze River is in the central area of the Qinghai-Tibet Plateau. This region is one of the typical areas for investigation of interactions among hydrology, ecology and meteorology. In recent years, under global climate changes, the shrinkage of lakes and wetlands, the degradation of meadows and the melting of permanent frozen soils have threaten the whole plateau and the Yangtze River Basin (Kang *et al.*, 1999; Wang and Chen, 2001; Chen *et al.*, 2002; Lu *et al.*, 2005; Yang *et al.*, 2007; Zhang and Gao, 2007). These problems give rise to concerns on the source region of the Yangtze River from inter-

national society and academia.

The change of runoff in river basins at regional scales is regarded as an indicator of local eco-hydrological response to global climate change. As the sub-surface component of runoff, baseflow has a unique importance in the studies of seasonal and annual flow patterns and ecological water demand in river basins (Tallaksen, 1995; Yin *et al.*, 2004; Huang and Chen, 2005; Liu *et al.*, 2005; Chen *et al.*, 2006a; Aksoy *et al.*, 2008, 2009; Aksoy and Wittenberg, 2010), and can

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be complicatedly influenced by geological conditions, precipitation, temperature and landuse (Vogel and Kroll, 1992; Wittenberg, 1999, 2003; Wittenberg and Sivapalan, 1999; Zhang and Schilling, 2006; Aksoy and Wittenberg, 2011). As an example, it was found that the reduction of baseflow in the source region of the Yellow River is a composite result of climate conditions and human activities at multi-time scales, which can not be simply explained by linear trends of precipitation and air temperature (Chen *et al.*, 2006b; Liang *et al.*, 2007; Liang *et al.*, 2008). The relationship between runoff and climate in the source region of the Yellow River is typically implied in the periodical characteristics of streamflow, precipitation and air temperature (Liang *et al.*, 2010). The baseflow in the source region of the Yangtze River, that in the Tongtianhe River in particular, has not yet been well investigated. This region is cold and arid. Permanent and seasonal frozen soils are developed in the region and their thickness is largely determined by air temperature. Since precipitation and frozen soils play an essential role in groundwater flow, it can be expected that the baseflow of the Tongtianhe River is subject to

both precipitation and air temperature.

In this study, with relevant hydrological data for the source region of the Yangtze River, the long-term baseflow of the Tongtianhe River was abstracted by Kalinen separation method. Then the periodical characteristics of the baseflow were analyzed by Morlet wavelet method. The impacts of precipitation and air temperature on baseflow were investigated, as well to discuss the trend of change.

1 Study area

The source region of the Yangtze River is located in the central part of the Qinghai-Tibet Plateau with a catchment area of 158,500 km², falling within 32°26'–35°46'N and 90°33'–95°20'E (Fig. 1). The main stream in the region is the Tongtianhe River, which is one of the upstream branches of the Yangtze River. The Tuotuohe River and Chumaer River are two relatively large branch rivers in the upstream area of the Tongtianhe River. The river basin is bounded by the Tanggula Mountains and Kunlun Mountains. The regional altitude ranges from more than 6,000 m in the west to lower than 4,000 m in the east, but is generally

Fig. 1 The source region of the Yangtze River

higher than 3,600 m. The mean annual air temperature is about -4.2°C , and the mean annual precipitation approximates 354 mm. Total precipitation is mainly contributed by rainfall in the summer but snow, sleet and hail in the other seasons also play an important role in contribution to annual precipitation. On average, the annual relative humidity ranges between 55% and 60%, and the annual potential evaporation is about 1,317 mm (Hu *et al.*, 2009).

The metrological data in this region are obtained from four meteorological stations called Tuotuohe station, Qumalai station, Yushu station and Wudaoliang station (Fig. 1). Near the east boundary, a hydrological station, Zhimenda station, is located close to the meteorological station at Yushu. Meteorological and hydrological data from 1957–2009 are available at the stations. The hydrological station is in the outlet of the source region, so that the runoff of the Tongtianhe River can be observed. And the rivers (Tuotuohe River, Chumaer River, *etc.*) converge into Tongtianhe River at the outlet and then discharge out of the region. Thus, the observed data can reflect the change of runoff in the whole source region of the Yangtze River.

2 Methods

2.1 Development of baseflow separation method

According to hydro-geological conditions and baseflow processing of different catchments, various methods have been raised by researchers. They can be classified into such methods as graphic analysis, numerical simulation, hydrological modeling, physical chemistry and mathematical physics. The experience-based graphic analysis method is to separate hydrograph geometrically, including linear horizontal separation and linear slant separation. By consideration of simplicity and subjectivity of the graphical approach, and combining with computer technology and signal processing, the numerical simulation method was raised, which mainly includes filtering and Kalinen separation. However, the hydrological meaning of parameters for this method is not explicit, as it has not been confirmed completely. The hydrological modeling method is to apply hydrological circulation to calculate each part of water balance. With the development of isotope monitoring technology, physical chemistry method is introduced to use isotope tracer to calculate the ratio

of baseflow in runoff. Because of the strict requirements of monitoring instruments and regional hydrological conditions, it has not yet been applied widely. All the above methods have not been quite used as solutions to the baseflow production mechanism. Thus based on formula derivation and mechanism model establishment, the mathematical physics method is widely studied, the representative of which is the hydrodynamic approach (Qian *et al.*, 2011a).

2.2 Modified Kalinen baseflow separation method

The feature of flood recession curve has a close relationship with the basin water conservation characteristics in a watershed and has been applied in the analysis of baseflow. Generally, the decaying of the flood (Q) has an exponential relationship with elapse time step (t), as follows:

$$Q(t) = Q_0 \exp(-\alpha t). \quad (1)$$

Where, Q_0 is the initial flow rate for the break point at the beginning of recession; α is the recession index which reflects the release of subsurface runoff. The recession index can be estimated through a logarithm linear diagram of recession curve if the break point is appropriately chosen.

The ratio of subsurface runoff to surface runoff, B is another essential parameter in baseflow separation analysis defined as:

$$B = \frac{Q_{sub}}{Q_{sur}}, \quad (2)$$

$$Q_{sur} = Q_{total} - Q_{sub}. \quad (3)$$

Where, Q_{sub} and Q_{sur} represent subsurface runoff and surface runoff, respectively; Q_{total} is total runoff. The determination of the ratio involves a test process to ensure that the baseflow is always not larger than the observed total runoff.

In estimating variable subsurface runoff, Kalinen (Jin, 1982) suggested an equation as follows:

$$\begin{aligned} Q_{sub, t} &= Q_{sub, t-1} + B\alpha Q_{sur, t-1}\Delta t - (1+B)\alpha Q_{sub, t-1}\Delta t \\ &= B\alpha Q_{sur, t-1}\Delta t + (1 - ((1+B)\alpha\Delta t))Q_{sub, t-1}. \end{aligned} \quad (4)$$

Where $Q_{sub, t}$ and $Q_{sub, t-1}$ are subsurface runoff at discrete time (time step) t and $t-1$, respectively. This method was improved by considering a lumped effect of previous runoff on present runoff (Zhang, 1985), as given by:

$$Q_{sub, t} = \theta \left[\begin{matrix} Q_{sur, t-1} + \lambda Q_{sur, t-2} + \\ \lambda^2 Q_{sur, t-3} + \dots + \lambda^{t-2} Q_{sur, 1} \end{matrix} \right] + \lambda^{t-1} Q_{sub, 1} \quad (5)$$

Where $\theta = B\alpha\Delta t$ and $\lambda = 1 - (1+B)\alpha\Delta t$. Furthermore, the equation was simplified by Chen *et al.* (2006c) as follows:

$$Q_{sub, t} = \theta Q_{sur, t-1} + \lambda Q_{sub, t-1} \quad (6)$$

Where θ and λ have the same representation as in Eq. 5. This modified Kalinen separation method has shown its efficiency in practice (Chen *et al.*, 2006c). The determination of the two unknown parameters, α and B , is based on the analysis of monthly runoff data and results in variable parameter values that have been reported by Qian *et al.* (2011b). In addition, the advanced Kalinen baseflow separation method is used well in catchments little influenced by human activities, such as the source region of the Yangtze River (Chen *et al.*, 2006b, c; Liang *et al.*, 2007; Liang *et al.*, 2008; Qian *et al.*, 2011b). Thus, the annual baseflow taken for analysis in this study is derived from monthly data.

2.3 Wavelet method

Wavelet method is a powerful method in analyzing time signal series at different periodical and frequency domains. It has been widely applied in the community of geosciences (Grossman and Morlet, 1984; Guyodo *et al.*, 2000). In particular, it is efficient for the analysis of long-term time series such as temperature, precipitation, humidity, and extreme climatic phenomena including ENSO (El Niño Southern Oscillation), SOI (Southern Oscillation Index) and NAO (North Atlantic Oscillation) (Compagnucci *et al.*, 2000; Labat, 2005). The periods or frequencies of streamflow have also been studied by wavelet transformation (Coulibaly and Burn, 2004; Labat *et al.*, 2005; Adamowski and Sun, 2010; Kisi, 2010). In comparison with Fourier analysis, wavelet transformation is more effective in providing fine time resolutions for long duration signals and fine frequency resolutions for high frequency signals (Bazayit and Aksoy, 2001; Hsu, 2010). Wavelet method is, therefore, a better choice in the study of multi-scale and non-stationary properties of precipitation, temperature and baseflow over finite spatial and temporal domains. Thus, to reveal the periodical characteristics of baseflow in this study area and analyze the relationship between runoff, precipitation and air tem-

perature, wavelet method was used.

On the basis of a time series or a continuous function, $f(t)$, the time-scale coefficient $C(a, \tau)$ is derived by wavelet transformation, being defined as follows (Labat, 2008):

$$C(a, \tau) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t) \psi^* \left(\frac{t-\tau}{a} \right) dt \quad (7)$$

Where, ψ^* is the complex conjugate of the wavelet function ψ , which can be real or not; a and τ are the scale and shift time, respectively; $C(a, \tau)$ represents the conditional correlation between the wavelet function ψ and time signal series $f(t)$. The parameters a and τ are used to change the location and shape of ψ .

The wavelet transformation can be operated with different types of wavelet function ψ , such as the Morlet wavelet, the Haar wavelet and the Mexican Hat wavelet. After the experiments of the abovementioned wavelet functions, the Morlet wavelet was employed in this study. In one dimension, the Morlet wavelet is defined as follows (Kumar and Foufoula-Georgiou, 1997):

$$\psi(t) = \pi^{-1/4} \left[\exp(-i\omega_0 t) - \exp(-\omega_0^2/2) \right] \exp(-t^2/2), \quad (8)$$

which is a complex Morlet wavelet. Indeed, the real part of this complex Morlet wavelet is commonly used and its most popular form is:

$$\psi(t) = \pi^{-1/4} \exp(-t^2/2) \cos(\omega_0 t). \quad (9)$$

Where ω_0 is a non-dimensional constant which allows an exchange between time and frequency resolution, $\omega_0=5$ being generally applied. Because of the relatively narrow frequency domain and the relatively wide time domain, the Morlet wavelet can extract fine structures from the time series based on a cluster analysis (Kirby and Swain, 2004). In this study, the real Morlet wavelet (Eq. 9) was applied to obtain the real wavelet coefficient and the result was shown by a contours map of $C(a, \tau)$ along period scale (a) and shift time (τ).

3 Results and discussion

3.1 Baseflow estimation

As estimated with the modified Kalinen separation method, the annual mean baseflow in the source region of the Yangtze River is $5.74 \times 10^9 \text{ m}^3$ for the pe-

riod between 1957 and 2009. In comparison with the inner-annual variation of total streamflow, the baseflow shows a weaker fluctuation. The total flow is completely contributed by baseflow in winter from December to March, but the baseflow contributes 40%–70% of the annual runoff. The inter-annual change of the baseflow exhibits a positive trend after 1980. The variation of annual baseflow can be characterized with coefficient of variation (C_v), a parameter in statistics to indicate the dispersion of time series. Before the 1980s, it was in a steady state, with a variation coefficient of 24.7; and after then, it demonstrated dramatic variations and large amplitudes, with its variation coefficient being increased to 33.2. The annual baseflow reached a maximum value of $11.29 \times 10^9 \text{ m}^3$ in 1989 and a minimum value of $2.86 \times 10^9 \text{ m}^3$ in 1979 (Fig. 2).

In order to capture the long-term behavior of data, annual baseflow was selected for periodical analysis

with wavelet method. The results of wavelet coefficients and variance obtained by using real Morlet wavelet function are shown in Fig. 3. It can be found that the pattern of baseflow from 1957 to 2009 is characterized by a long-term trend and two significant periods. The three horizontal dashed lines in Fig. 3 represent the strong trends for the periods of 43 years, 21 years and 7 years, respectively. In this study, the trend for the longest period (43-year) can be considered as the trend of runoff or baseflow. At a scale of series data, the trend can be linear or fluctuating. Thus, it is reasonable to consider the longest 43-year period exhibits a fluctuating trend, the curve of which is smooth and stable.

The annual baseflow displays a long-term regularity, and its wavelet coefficient is at a local peak in around 1957, reaches a trough in around 1983, and then returns to local peak in around 2009. According to the trend, it can be predicted that the next local peak will

Fig. 2 Changes of annual baseflow and annual runoff in the source region of the Yangtze River

Fig. 3 Wavelet transformation of annual baseflow: contour map of wavelet coefficients and variance for different periods

appear in 2020. In comparison, the 21-year period turns to local peak in around 2009. According to the trend is significant, which represents strong fluctuations of annual baseflow. Its peak occurred in 1957, 1984 and 2009, respectively, while troughs came into being in 1971 and 1997. Differently, the 7-year period trend reached its peak in 1957, 1965, 1974, 1983,

1990, 2000 and 2009, and troughs emerged in 1961, 1969, 1979, 1986, 1995 and 2005, respectively.

Wavelet coefficients of the 43-year trend and the two significant periods were extracted to show further information, as shown in Fig. 4. It can be seen that the summation of the decomposed wavelet coefficients exhibits a similar pattern to the annual baseflow,

Fig. 4 Similarity between summation (b) of wavelet coefficients for 43-year, 21-year and 7-year periods (a) and baseflow (c)

which demonstrates the efficiency of Morlet wavelet in capturing the dominative periods of baseflow. Furthermore, the summation curve takes a ‘W’ shape, which means that the baseflow follows the sequence of descending–ascending–descending–ascending.

3.2 Impacts of precipitation and temperature

The Morlet wavelet method was applied for precipitation and temperature data analysis, in an aim to probe into the impacts of the two factors on the baseflow in the source region of the Yangtze River. Precipitation and air temperature data for the same period are available at the four meteorological stations. In view of regional hydrological features, the Thiessen Polygon method was used in zone division (Fig. 1) to estimate average precipitation and temperature. The average values of precipitation (P_{avg}) and air temperature (T_{avg}) were calculated as follow:

$$P_{avg} = 0.48 \times P_{tth} + 0.26 \times P_{qml} + 0.05 \times P_{ys} + 0.21 \times P_{wdl}, \quad (10)$$

$$T_{avg} = 0.48 \times T_{tth} + 0.26 \times T_{qml} + 0.05 \times T_{ys} + 0.21 \times T_{wdl}. \quad (11)$$

Where the subscripts *tth*, *qml*, *ys* and *wdl* represent the names of the meteorological stations, i.e. Tuotuohe, Qumalai, Yushu and Wudaoliang, respectively. After that, the wavelet coefficients of P_{avg} and T_{avg} from 1957 to 2009 were obtained by the same method applied in baseflow analysis.

Precipitation acts as the dominative control of baseflow because it is the ultimate source of subsurface runoff. As a result, the annual baseflow is generally proportional to the annual precipitation. In contrast, the impact of air temperature seems more complex and indirect. Air temperature can influence the forms of precipitation, regional evaporation and special hydro-geological conditions, such as the frozen soils in this cold region. It is expected that the Morlet wavelet transformation can reveal how baseflow is affected by these climatic factors in the source region of the Yangtze River. Thus, the relationship between baseflow, precipitation and air temperature was investigated in the time-frequency space with normalized wavelet coefficients.

As shown in Fig. 5, the relationship among baseflow, precipitation and temperature was implied in the correlation between their normalized wavelet coefficients

at different temporal scales. Figures 5 (a) and (b) show significant positive linear correlations both between precipitation and baseflow (correlation coefficient is 0.98) and between temperature and baseflow (correlation coefficient is 0.90) for the 43-year wavelet coefficients. The correlations suggest that the long-term increasing trends of precipitation and air temperature lead to an increasing trend of baseflow. For the wavelet coefficients of 21-year and 7-year periods, the positive linear correlation between precipitation and baseflow is significant, as shown in Figs. 5c and 5e. However, the correlation between air temperature and baseflow is not so evident, especially for the 21-year period (Figs. 5d, 5f).

To make an integrated analysis of the correlation result, the multivariate linear regression method was applied. The summarized wavelet coefficient of baseflow, as shown in Fig. 4b, was assumed to be the linear combination upon normalized wavelet coefficients of precipitation and air temperature. Since the correlation between 21-year coefficients of temperature and baseflow is very weak, the air temperature for the 21-year period was not taken into account. The final result can be expressed as:

$$C_{BF} = 0.72P_{43} + 2.32P_{21} + 1.06P_7 - 0.18T_{43} + 0.32T_7. \quad (12)$$

Where, C_{BF} is the wavelet coefficient summation of baseflow shown in Fig. 4b; P_{43} , P_{21} and P_7 represent the normalized wavelet coefficients of precipitation for 43-year, 21-year and 7-year periods, respectively; T_{43} and T_7 represent normalized wavelet coefficient of temperature for 43-year and 7-year periods, respectively. According to the regression coefficients in Eq. (12), the change of annual baseflow was contributed mostly by the change of precipitation (88.4%) and secondly by the change of air temperature (11.6%). To be specific, the contribution ratios of precipitation change for 43-year, 21-year and 7-year periods are 15.5%, 50.1% and 22.8%, respectively, and the contribution ratios of air temperature change for 43-year and 7-year periods are 3.9% and 7.7%, respectively.

4 Conclusions

With modified Kalinen baseflow separation method, the baseflow in the source region of the Yangtze River was estimated, and the periodical characteristics of baseflow were revealed by real Morlet wavelet meth-

Fig. 5 Correlations of the normalized wavelet coefficient (C) between baseflow and precipitation and air temperature for the periods of 43-year (a, b), 21-year (c, d) and 7-year (e, f)

od. The results show that there are three significant trends existing on 43-year, 21-year and 7-year periods. The most powerful trend is for the 21-year period. Simple summation of the wavelet coefficients for these three significant periods shows a similar change pattern with respect to the wavelet coefficient of baseflow. It demonstrates that Morlet wavelet is efficient in capturing the dominative periods of hydrological series.

Annual precipitation and annual air temperature were analyzed as well with the real Morlet wavelet method by taking into consideration their impacts on annual baseflow. Their wavelet coefficients are normalized and the results of the typical trends for

43-year, 21-year and 7-year periods were selected for correlation analysis. The result indicates that an approximate linear positive correlation between baseflow and precipitation for all periods exists. However, the correlation between baseflow and air temperature is significantly weak, except for the 43-year period. A linear regression equation was used to estimate the wavelet coefficient of baseflow based on wavelet coefficients of precipitation and air temperature. The regression coefficients indicate that the change of annual baseflow was contributed mostly by the change of precipitation (88.4%) and secondly by the change of temperature (11.6%).

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Eight new records of birds found in Xinjiang in 2011

In 2011, eight new records of birds were found in Xinjiang Uygur autonomous region, including Glossy Ibis (*Plegadis falcinellus*), Japanese Sparrowhawk (*Accipiter gularis*), White-naped Crane (*Grus vipio*), Red-rumped Swallow (*Hirundo daurica*), Bar-tailed Treecreeper (*Certhia himalayana*), Azure-winged Magpie (*Cyanopica cyana*), Eastern Crowned Willow Warbler (*Phylloscopus coronatus*) and Black-faced Bunting (*Emberiza spodocephala*). Half of them were recorded by bird-watchers and photography lovers.

The appearance of some birds is occasional in West China, such as the Glossy Ibis, which is small in population in China and was first recorded in the border regions of Kashi, indicating that the bird is probably from neighbor countries. It has also been an occasional event for the White-naped Crane, a species under national key protection and originally lives in Northeast China, to appear in western Xinjiang by intermixing among Common Cranes.

Observers, by means of improved field monitoring, are able to collect specimens through telescopes and telephoto cameras. A steady annual increase in the number of bird records can thus be expected. The recording of Bar-tailed Treecreeper (*Certhia himalayana*), for instance, has been a hard task due to the mystery of the species. Other species exhibit an obvious tendency of inhabitation expansion probably due to their migration route alterations triggered by global climate change.

The invasion of some specific exotic species into Xinjiang is completely related with anthropogenic factors. In recent years, some alien species bought from the market have been set free, contaminating local biological genetic diversity. The strong adaptability of certain species may go so far as to pose a threat on their counterparts native in Central Asia.