MULTI-SCALE MODELING OF THE RESPONSE OF RUNOFF TO CLIMATE CHANGE

by

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With global warming, climate change has tremendously changed the hydrological processes. To discover the non-linear trend of the natural runoff and its response to precipitation and temperature in the Yellow River Basin, the non-linear relationships among the runoff, precipitation and temperature are analyzed by the wavelet decomposition and reconstruction methods, partial correlation analysis and multiple linear regression analysis. The main findings of this study are: (1) The annual natural runoff, precipitation and temperature have the similar periods (27-year, 12-year), which indicates that the periodicity of the natural annual runoff has closely relationship with the regional climate change. (2) The annual runoff, precipitation and temperature exhibit five patterns non-linear variations at five time scales (1, 2, 4, 8, 16 years), that is to say, their non-linear trends are scale-dependent with time. (3) The annual natural runoff has a significant positive correlation with the precipitation and has a negative correlation with temperature. In addition, the runoff variation is more sensitive to change in precipitation than the change in temperature at all the five time scales. (4) Although the runoff and the climate change factors have non-linear trends at different time scales, the runoff has linear correlation with the temperature and the precipitation, especially at a large time scale.

Key words: *temperature, climate change, runoff, precipitation, wavelet analysis, multi-scale*

Introduction

With global warming, climate change has greatly changed the regional hydrological cycles [1, 2]. Assessment of the hydrological response to climate change has recently attracted widely concerns [3]. Especially in China, a number of studies show that there is an abrupt point in the hydrological and climate processes in Northwest China after 1980s [4]. The Yellow River, as the second largest river in China, is one of the regions facing serious water shortages due to dry climate and increasing water demand [5]. Assessing the impact of climate change on the runoff is important for water resources planning and management.

Two methods, *i. e.*, the method based on hydrological modeling and the method based on climate elasticity are often used to evaluate the effects of climate change on the runoff. The hydrological modeling method usually has uncertainties due to the complexity in determining the parameters and the structure of the hydrologic model [6]. The method based on

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climate elasticity is simpler and has been verified to be an effective one in quite a few researches [7]. However, this method only gives the result at a single scale. Due to the apparent changes in the climatic-hydrological process, complex relationship between climate change and hydrologic process should be thoroughly studied at different timescales [8]. Analyzing of the multiple response of runoff to climate change is vital to long-term watershed management of global warming scenarios. In addition, more studies are needed to explore the non-linear characteristics of hydro-climatic processes from different perspectives. For these reasons, the aims of this paper are: (1) to discover the variation trends and periods of the annual natural runoff, annual average precipitation and temperature in the Yellow River Basin (YRB), (2) to identify the non-linear relationship between the natural runoff and the climate factors at multiple scales, and (3) to investigate the response of climate change to the runoff.

Study area and data

In the past few decades, the natural runoff in the Huayuankou station had a significant decreasing trend [9]. The study area selected in this study is the region upward the Huayuankou station in the YRB. The annually mean precipitation and temperature data during 1957-2000 are collected from 72 meteorological stations supplied by the China meteorological data sharing service system (fig. 1). The natural runoff data collected from the Yellow River Conservancy Commission instead of the observed runoff data are used, which are computed by removing human impacts from the observed data. The areal precipitation and temperature are calculated from the data of 72 meteorological stations based on the Thiessen polygon theory. For simplicity, we use *R*, *P,* and *T* to denote the annual natural runoff, areal precipitation and temperature of the study area, respectively.

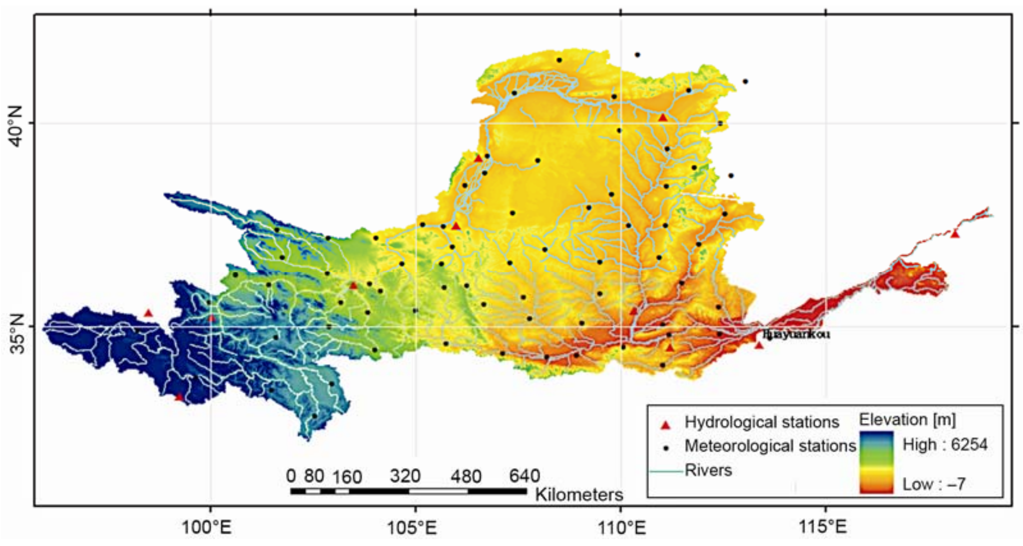

Figure 1. Locations of meteorological and hydrological stations in the Yellow River Basin

Methods

In this study, the continuous wavelet transform (CWT) and discrete wavelet transform (DWT) are employed to analyze variations, periodicities, trends and multi-scale approximations in climatic and hydrological time series. For more details of CWT and DWT, please refer to [10]. The aim of this study is identifying the response of *R* to *P,* and *T* at different time scales, the overall process of the modeling framework are:

Step 1. Identify the period in *R*, *P,* and *T* using CWT method and wavelet variance.

Step 2. Non-linear trends of *R*, *P,* and *T* are approximated based on DWT at the time scales (2, 4, 8, 16 years). The time series obtained by the wavelet approximation are denoted as *S1*, *S2*, *S3,* and *S4*, respectively. The original time series is denoted as *S0*.

Step 3. The correlation analysis is used to check the correlations among *R*, *P,* and *T* at the five time scales (1, 2, 4, 8, 16 years).

Step 4. Wavelet regression analysis is employed to establish the complex relationship among *R*, *P,* and *T* at different timescales.

Results and discussion

Periodicity of annual runoff and climate change

Figure 2 shows the data of the areal *R*, *P,* and *T* obtained by Thiessen polygon interpolation. It is difficult for us to identify the trends (*e. g*. periodicity) from fig. 2. Based on the wavelet analysis, the CWT is applied to analyze the time series of *R*, *P,* and *T*. Figure 3 shows the contour map of the real part of the wavelet coefficients of *R*, *P,* and *T*. In fig. 3, the coefficients with negative values denote a wet year, the rain is heavy and the temperature is in cold stage. Conversely, the coefficients with positive values denote a dry year, lack of rain and the temperature is in warm stage. *R*, *P,* and *T* have a remarkably interannual and interdecadal variation. There are 27-year, 12-year, 8-year, and 5-year periods for *R*, and *P* has the similar periods with *R*. The periods of 27-year and 12-year are the two main periods for *R* and *P*. These results can be also easily seen from fig. 4. Similarly, the annual average temperature also has the period of 27-year. These results imply that there is a 27-year cycle for all the three time series and other periods are approximate, which indicates that the periodicity of the natural annual runoff has closely relationship with the climate change.

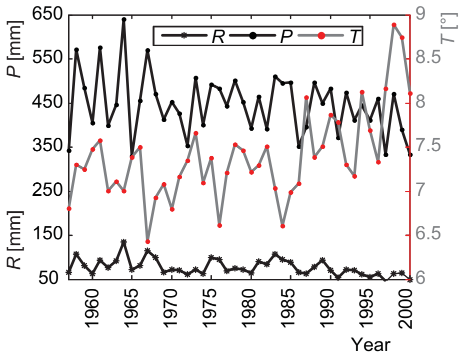

Figure 2. The data of *R*, *P,* and *T* of the study area

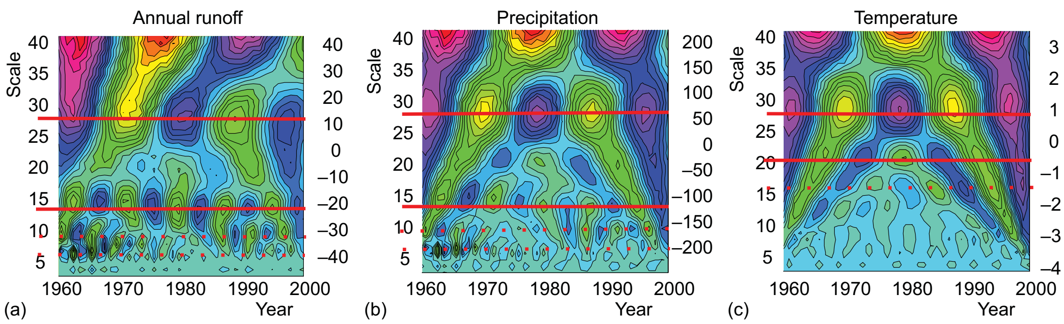

Figure 3. Contour maps of the real part of the wavelet coefficients of three time series: (a) runoff, (b) precipitation, and (c) temperature

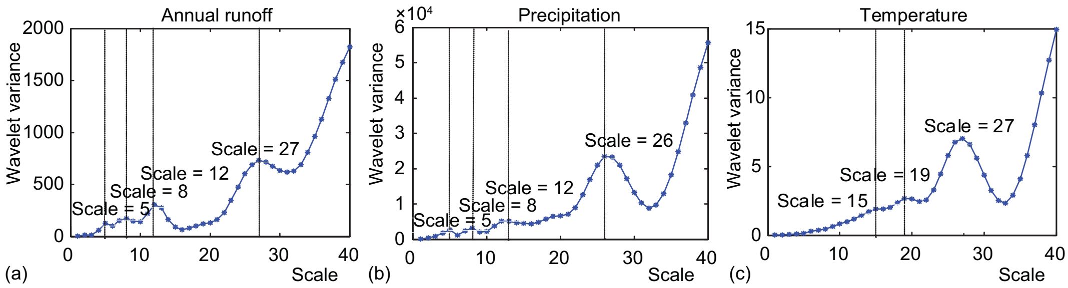

Figure 4. The wavelet variance diagrams: (a) annual runoff, (b) precipitation, and (c) temperature

Non-linear trends of R, P, and T based on wavelet analysis

The non-linear trends for the runoff process and the climate factors are analyzed at multiple time scales based on the DWT. Both the hydrological and meteorological time series are decomposed into four approximations at different timescales of the non-linear trends (fig. 5). Results show that: (1) The *S1* curve (at the 2-year scale) contains the main information of the original signal, and the curves are getting much smoother and the increasing trend becomes more obvious as the scale level increases. (2) *R* and *P* have similar decreasing trends, but *T* has an increasing trend. (3) The peaks and valleys of the four time series of *R* are consistent with *P*, which indicates that *P* is the main factor affecting the decreasing trends of *R*. (4) *R*, *P,* and *T* exhibit different non-linear variations at the time scales (2, 4, 8, 16 years). That is to say, non-linear trends of *R*, *P,* and *T* are dependent on time scales.

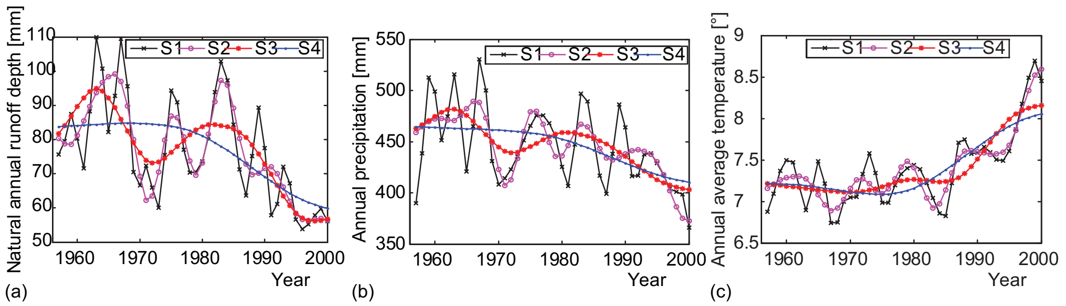

Figure 5. Wavelet approximations for *R*, *P*, and *T* at different timescales: (a) *R*, (b) *P*, and (c) *T*

Results of the correlation and multiple linear regression analysis

The correlations between the annual runoff and the climate factors are examined *via* correlation and multiple linear regression analysis. Table 1 shows the correlation and partial correlation coefficients among *R*, *P,* and *T* at the five time scales. The standardized regression equations of *R*, *P,* and *T* are shown in tab. 2. Results of correlation coefficients show that there is a significant positive correlation between *R* and *P*, and *R* is significant negatively related to *T* for all the five time scales. The partial correlation coefficients between *R* and *T* of *S2* and *S3* have no significant difference, which indicates that *T* has no obvious influence on *R* at the 4-year and *8*-year time scales. The regression results show that: (1) All of the regression models are significant at $\alpha = 0.001$, and correlation coefficients (R^2) range from 0.714 at the short-term timescale to 0.999 at the long-term timescale. High R^2 values indicate that R is significantly correlated with P and T. (2) The runoff is more sensitive to the precipitation than the temperature at all of the time scales, this can be easily seen from the standardized regression coefficients. (3) The multi-regression models generated from the multiple timescales show the relationship among R, P, and T at different time scales, which can be considered as a supplement to other studies.

Table 1. The correlation and partial correlation analysis between *R, P,* and *T* at different time scales

Time scales	Correlation analysis			Partial correlation analysis	
	(R, P)	(R, T)	(P, T)	(R, P)	(R, T)
S0	0.793	–0.528	*–0.27	0.796	–0.535
S1	0.802	0.704	–0.576	0.684	–0.495
S2	0.888	–0.798	–0.84	0.666	*–0.209
S3	0.992	–0.872	–0.864	0.967	*–0.226
S4	0.996	–0.986	–0.968	0.986	–0.953

Note: the digit marked with * means no significant correlation.

Table 2. Multiple linear regression analysis of *R, P,* and *T* for all the five time scales

Time scales	Standardized regression equations	R^2	F	Significance level
S0	$R = 0.702P - 0.339T$	0.714	52.923	0.001
S1	$R = 0.594P - 0.361T$	0.731	55.715	0.001
S2	$R = 0.739P - 0.177T$	0.798	80.828	0.001
S3	$R = 0.942P - 0.058T$	0.984	1293.803	0.0001
S4	$R = 0.655P - 0.352T$	0.999	26019.77	0.0001

Conclusions

To analyze the non-linear trends in annual R and its response to P and T at different time scales on a large basin scale, a new combination model based on CWT and DWT as well as multiple linear regression analysis and partial correlation analysis was proposed in this paper. The main conclusions are:

- R, P, and T have the similar periodicity of 27-year cycle and 12-year cycle, which indicates that the periodicity of the natural annual runoff has closely relationship with the regional climate change.
- R, P, and T exhibit five patterns non-linear variations for all the five time scales (1, 2, 4, 8, 16 years), that is to say, their non-linear trends are scale-dependent with time.
- R has a significant, positive correlation with P and has a negative correlation with T at all the five time scales.
- Although the runoff and the climate change factors have non-linear trends at different scales, the runoff has linear correlation with the temperature and the precipitation. All these results will contribute to the long-term watershed management on a large basin scale.

Acknowledgments

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