Science of the Total Environment 601–602 (2017) 1449–1465

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Quantitative assessment of the impacts of climate change and human activities on runoff change in a typical karst watershed, SW China

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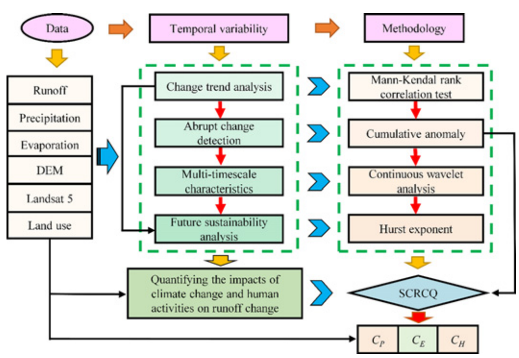
HIGHLIGHTS

- We evaluated the impact of climate change and human activities on runoff changes.
- Climatic factors highly contributed to runoff change.
- The impact of precipitation on runoff change was stable.
- The contribution of human activities to runoff change was low.
- We provided a understanding of the main factors that contribute to runoff change.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 18 January 2017
Received in revised form 31 May 2017
Accepted 31 May 2017
Available online 8 June 2017

Editor: D. Barcelo

Keywords:
Climate change
Human activities
Runoff
Contribution
Land use
Karst

ABSTRACT

The Yinjiang River watershed is a typical karst watershed in Southwest China. The present study explored runoff change and its responses to different driving factors in the Yinjiang River watershed over the period of 1984 to 2015. The methods of cumulative anomaly, continuous wavelet analysis, Mann-Kendall rank correlation trend test, and Hurst exponent were applied to analyze the impacts of climate change and human activities on runoff change. The contributions of climate change and human activities to runoff change were quantitatively assessed using the comparative method of the slope changing ratio of cumulative quantity (SCRCQ). The following results were obtained: (1) From 1984 to 2015, runoff and precipitation exhibited no-significant increasing trend, whereas evaporation exhibited significant decreasing trend. (2) In the future, runoff, precipitation, and evaporation will exhibit weak anti-persistent feature with different persistent times. This feature indicated that in their persistent times, runoff and precipitation will continuously decline, whereas evaporation will continuously increase. (3) Runoff and precipitation were well-synchronized with abrupt change features and stage characteristics, and exhibited consistent multi-timescale characteristics that were different from that of evaporation. (4) The contribution of precipitation to runoff change was 50%–60% and was considered high and stable. The contribution of evaporation to runoff change was 10%–90% and was variable with a positive or negative effects. The contribution

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http://dx.doi.org/10.1016/j.scitotenv.2017.05.288

of human activities to runoff change was 20%–60% and exerted a low positive or negative effect. (5) Climatic factors highly contributed to runoff change. By contrast, the contribution of human activities to runoff change was low. The contribution of climatic factors to runoff change was highly variable because of differences among base periods. In conclusion, this paper provides a basic theoretical understanding of the main factors that contribute to runoff change in a karst watershed.

1. Introduction

In recent decades, global climate change and human activities have accelerated the global hydrological cycle (Allen and Ingram, 2002; Stocker and Raible, 2005; C.Y. Xu et al., 2013; X.L. Xu et al., 2013a; X.L. Xu et al., 2013b; Millan, 2014; Amin et al., 2017) and have changed the spatiotemporal patterns of rainfall and evaporation (Beniston, 2002; Coulibaly, 2006; Chu et al., 2008; Hsu and Li, 2010; Liang et al., 2011; Liu et al., 2014). Thus, the runoffs of many rivers around the world exhibit a significantly decreasing trend (Fu et al., 2004; Xu et al., 2010; Wang et al., 2012a; Li and Zhou, 2016; Zhang et al., 2016) that greatly threatens global water security. In the karst watershed in Southwest China, prominent runoff attenuation has triggered a serious water crisis that threatens water resources and ecological security (Qin et al., 2015), as well as influences the survival and development of the 0.22 billion people in this region. Therefore, investigating the changing characteristics of runoff and quantitatively assessing the effects of climate change and human activities on runoff change in the karst watershed is crucial. Solving the water crisis in the karst watershed is conducive to water resources planning and management and has vast strategic significance in global water security.

Quantifying the impacts of climate change and human activities on runoff change has become a hot topic in climatic and hydrologic researches (Li et al., 2016; Yuan et al., 2016; Zhang et al., 2016). Previous reports have indicated that that human activities have altered the water cycle and have increased runoff loss. Researchers have utilized many methods to evaluate the contribution rates of the main influencing factors to runoff changes and have revealed that runoff changes involve the superposition of the effects of climate change and human activities, with human activities being the dominant factor (Beniston, 2012; Zhan et al., 2013; Gao et al., 2017). The effects of climate are mainly reflected in the inter-annual variability, multi-timescale, and future sustainability of runoff. The hydrological model and quantitative evaluation method are the main methods for the quantitative separation of the impacts of climate change and human activities at the watershed scale (Wang, 2014). In the former method, hydrological models are used to assess the influence of climate and human activities on runoff change by runoff simulation. The latter method is based on the methods of climatic elastic coefficient (Hu et al., 2012), multivariate regressive (Xu, 2011), sensitivity analysis (Zuo et al., 2013), water balance (Wang et al., 2009), and double mass curve of runoff and precipitation (Guo et al., 2014; Zhao et al., 2014; Niu et al., 2016). Many researchers have conducted a wide range of studies on the Yangtze River basin (Zhao et al., 2015), Yellow River basin (S.J. Wang et al., 2014; Kong et al., 2016), Wei River basin (Huang et al., 2016a), Hei River basin of China (K.S. Luo et al., 2016), as well as on several typical watersheds in other countries (Buendia et al., 2016; Zare et al., 2016; Farenhorst et al., 2017; Griffioen, 2017; Marcos et al., 2017). Based on their findings, runoff changes involved the superposition of the effects of climate change and human activities, and human activities was the dominant factor. Although these studies have quantitatively evaluated the comprehensive effects of climate change and human activities on runoff change, some shortcomings and deficiencies in research methods and research areas have been observed. For example, although the hydrological model has a good physical foundation, its structure and parameter sensitivity possess several uncertainties (Leavesley, 1994). Unverified simulation results likely overestimate the effect of climate change on runoff change (Legesse et al., 2003). Furthermore, although the quantitative evaluation method requires less data, a longer data series is needed to reach the effect of quantitative assessment, and the noise in the long-time data series interferes with the evaluation results (Sankarasubramanian et al., 2001). Eliminating the influence of inter-annual fluctuations is also difficult. The factors that affect runoff change and their specific contributions to runoff change in a karst watershed are significantly different from those in a non-karst watershed because of special hydro geographical structures and complex humanistic background (Kong et al., 2007; Bai et al., 2010; Patterson et al., 2013; Liu et al., 2016). Thus, the identification of main driving factors of water resource change and their contributions to runoff change in a karst watershed by water resource researchers and managers remains difficult. Quantifying the contributions of the major influencing factors in climate and human activities to runoff change in a karst watershed is now a major problem.

Runoff in a karst watershed has received little attention so far, with most studies focusing only on the research and development of water resources utilization technology (Hartmann et al., 2014; Qin et al., 2015; G.J. Luo et al., 2016), runoff simulation (Meng et al., 2015; Tian et al., 2016), and soil and water loss (J.X. Wang et al., 2014; Chen and Lian, 2016). Given the lack of theoretical basis, good technical methods, and data support, researchers have seldom considered the trend, periodicity, and future change of the hydrological and climatic factors in a karst watershed and have ignored the impacts of climate change and human activities on runoff change. International research on karst watersheds is not only short of relevant data but also lack experience and contribution. Therefore, the main contribution of the present study is the identification of the main contributing factors to runoff change in a typical karst watershed. Furthermore, the present study establishes a basic theoretical understanding of the influential mechanisms and contribution values of runoff change is established in a karst watershed with the support of hydrological and meteorological data from a long period of 32 years.

In this study, a new separation method of slope changing ratio of cumulative quantity (SCRCQ) (Wang et al., 2012b) was used to conveniently eliminate the noise and separate the influence values of climatic factors and human activities on runoff change. Accumulative amount was introduced to decrease the influence of inter-annual fluctuations in the measured data. Linear fitting between year and accumulation considerably improved the correlation coefficient of the fitting relationship. Cumulative anomaly (Wang et al., 2012a; Wang et al., 2012b) was used to accurately detect the abrupt change features of hydrological and climatic time series, thus avoiding the right avertence defect from double mass curve of runoff and precipitation (Ran et al., 2010) and the multi-point abrupt change from the non-parameter Mann-Kendall detection. The periodical influence and multi-timescale evolution features of hydrological and climatic time series were accurately reflected by continuous wavelet analysis, which was used for signal time-frequency analysis (Labat, 2008; Mustapha et al., 2013; Nourani et al., 2015; Rashid et al., 2015). The current changing trends of hydrological and climatic time series were accurately analyzed by the combined application of the Theil-Sen median trend analysis and Mann-Kendall rank correlation trend test method (Dong et al., 2009; Guo et al., 2011; Nalley et al., 2012; Araghi et al., 2016).

The Yinjiang River watershed, which is located in a typical karst valley area in Southwest China, was selected as the research site of the present study. This study combined Mann-Kendall rank correlation trend test, cumulative anomaly, continuous wavelet analysis, Hurst exponent, and SCRCQ to quantitatively evaluate the impacts of climate change and human activities on runoff change. The study has the following objectives: (1) to statistically detect the trends and the abrupt change points of hydrological and climatic time series of the watershed and to analyze its multi-timescale characteristics and future sustainability features, (2) to effectively separate the influential values of climate change and human activities on the runoff change and to quantitatively calculate the contributions of its main influential factors, and (3) to explore the influential mechanisms of the impacts of climate change and human activities on runoff change. This study provides a methodologies and data references for international counterparts for studying the impacts of climate change and human activities on runoff change in karst watershed. This study also provides new understanding for balancing the security pattern of global water resources.

2. Study site and materials

2.1. Study site

The Yinjiang River watershed (108°18′–108°47′ E, 27°53′–28°15′ N), which is located northeast of Guizhou Province (Fig. 1a), is a typical karst valley watershed in the Yinjiang County's karst test site. The watershed, which belongs to the Yangzi River system, is an important branch of the Wujiang River. It covers an area of 830 km^2, with an elevation range of 399–2465 m above sea level, and the mean elevation is 1033 m (Fig. 1b). The watershed's topography is mountainous. Elevation in the study area decreases from southeast to northwest, ranging in a large scope. The watershed is located the zone of humid subtropical monsoon climate, with an average annual temperature of 16.72 °C, average annual precipitation of 1103.44 mm/year, and average annual evaporation of 667.01 mm/year based on the 32 years (1984–2015).

The Yinjiang River watershed has particular geographical environment and complex hydrological process. The land surface is steep and broken with numerous underground cracks, causing a severe underground loss of runoff and rainfall. In addition, the situation of runoff depletion is very severe because of undulating terrain, small flow range, and low drainage density. The average annual runoff was only 4.62×10^8 m^3/year based on the 32 years (1984–2015). The middle of the watershed is located at the bottom of valley. A karst valley (Fig. 2a) with a geographical background of a syncline structure in the center of the valley with steep bedding slopes exists on both sides (Fig. 2b). Only one river exists in the valley area, the Yinjiang River, and it is the main channel. This river (Fig. 2a) passes through the bottom of the valley and has a large number of people and sloping farmlands distributed on both sides (Fig. 2b). It is an area with the largest intensity of human activities in the watershed. Although the Yinjiang River watershed has favorable water and temperature conditions, it is characterized by sparse vegetation coverage, thin and shallow soil, frequent human activities, severe water and soil loss, and intense evaporation. As a result, its runoff has gradually decreased.

2.2. Materials

Remote sensing data (P126, R40 and P126, R41), with a spatial resolution of 30 m, were selected for this work. These data include those extracted from Landsat 5 on 08-22-1990, 11-05-2000, and 11-01-2010, which were retrieved from the United States Geological Survey (USGS) website (http://earthexplorer.usgs.gov/). Meanwhile, digital elevation model (DEM) data, with a spatial resolution of 30 m, was provided by the International Scientific and Technical Data Mirror Site, Computer Network Information Center, Chinese Academy of Sciences (http://www.gscloud.cn).

Hydrological data were mainly monthly runoff of the Yinjiang River watershed (log data from 01-1984 to 12-2015). Meteorological data with the same length of time as hydrological data were mainly monthly precipitation and evaporation data. The monthly runoff and evaporation data were from the Guizhou Provincial Hydrology and Water Resources Bureau (http://www.gzswj.gov.cn/hydrology_gz_new/index.phtml). The monthly precipitation data for the study area were collected from eight stations from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/). The average annual precipitation data of each year for the watershed were interpolated by the Kriging method using ArcGIS 10 (ESRI 2010) with annual precipitation data of the precipitation observation stations in the watershed together with those from the neighboring observation stations outside it. The relative data in this study is standardized to simplify calculation and description in this study. Runoff, precipitation, and evaporation are simplified to be Q, P, and E for a convenient description, respectively.

3. Methodology

Five approaches were used in this study: Mann-Kendall rank correlation trend test, cumulative anomaly, continuous wavelet analysis, Hurst exponent, and SCRCQ. The specific steps of these approaches are

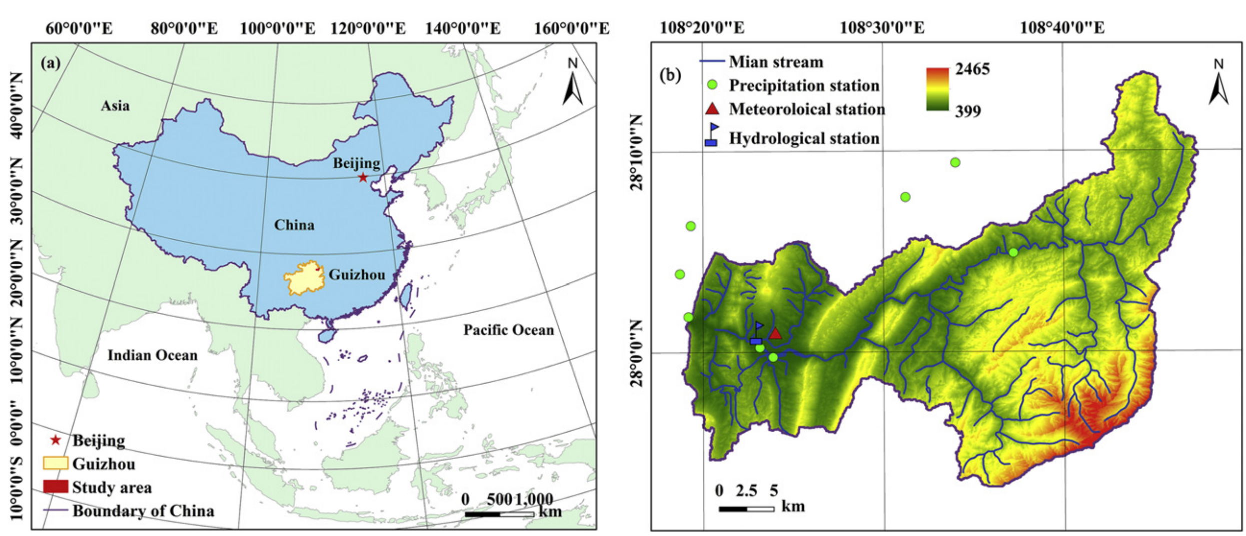

Fig. 1. Study area location in China (a) and the Yinjiang River watershed (b).

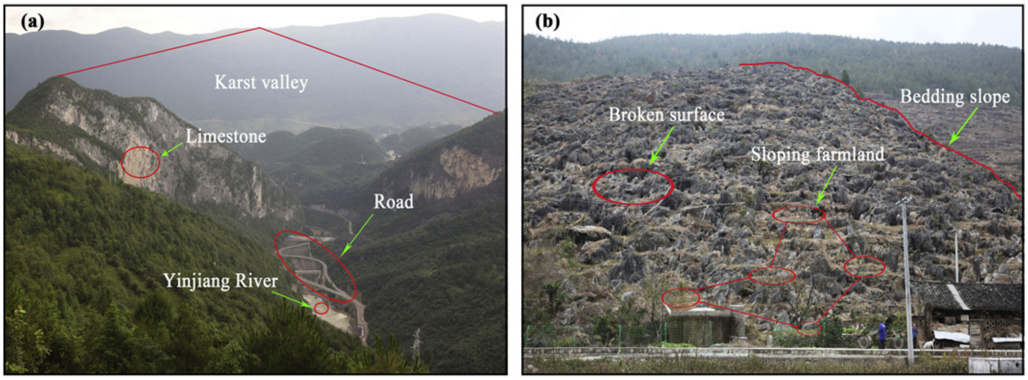

Fig. 2. Karst valley (a) and slope surface features (b) in the Yinjiang River watershed.

shown in Fig. 3. The Mann-Kendall rank correlation trend test was applied to detect changes in trends. Cumulative anomaly was used to detect the abrupt change times of runoff, precipitation, and evaporation. As a useful tool for the analysis of the time-frequency properties of various time series, continuous wavelet analysis was performed to identify periods in standardized runoff, precipitation, evaporation time series, and time-frequency correlations. Hurst exponent was used to detect long-term memory characteristics and future trends. The impacts of climate change and human activities on runoff change were calculated via SCRCQ based on the slope changes of the relations between years and accumulation of runoff, precipitation, and evaporation in different periods.

3.1. Mann-Kendall rank correlation trend test method

This study combines the Theil-Sen median trend analysis and the Mann-Kendall rank correlation trend test to analyze the time series. The Mann-Kendall rank correlation trend test method can quantitatively detect the changing trend of the time series (Adamowski and Bougadis, 2003; Pingale et al., 2013). It has been widely applied to analyze the trends and changes in sites with hydrological and meteorological time series. The formula is as follows:

$$\tau = \frac{4P}{N(N-1)} - 1 \tag{1}$$

$$\sigma_\gamma = \frac{2(2N+5)}{9N(N-1)} \tag{2}$$

$$Z = \tau/\sigma_\gamma \tag{3}$$

where Z refers to the rank correlation coefficient, the value of Z ranges from $-\infty$ to $+\infty$. P refers to the occurrence times of $R_j < R_i$ in all paired observed values of runoff (R_j, R_i, $j < i$), and N is the length of time series (32 years).

In terms of the Mann-Kendall rank correlation tend test, in the given α confidence level, $|Z \le Z_{(1-\alpha/2)}|$, the time series does not have a significant trend if the statistic amount $|Z \le Z_{(1-\alpha/2)}|$; the series has a significantly downward trend if $|Z < Z_{(1-\alpha/2)}|$; the series has a significantly increasing trend if $|Z > Z_{(1-\alpha/2)}|$. α refers to the level of significance. $\alpha = 0.05$, if $|Z_{(1-\alpha/2)}| = 1.64$; $\alpha = 0.01$, if $|Z_{(1-\alpha/2)}| = 2.32$.

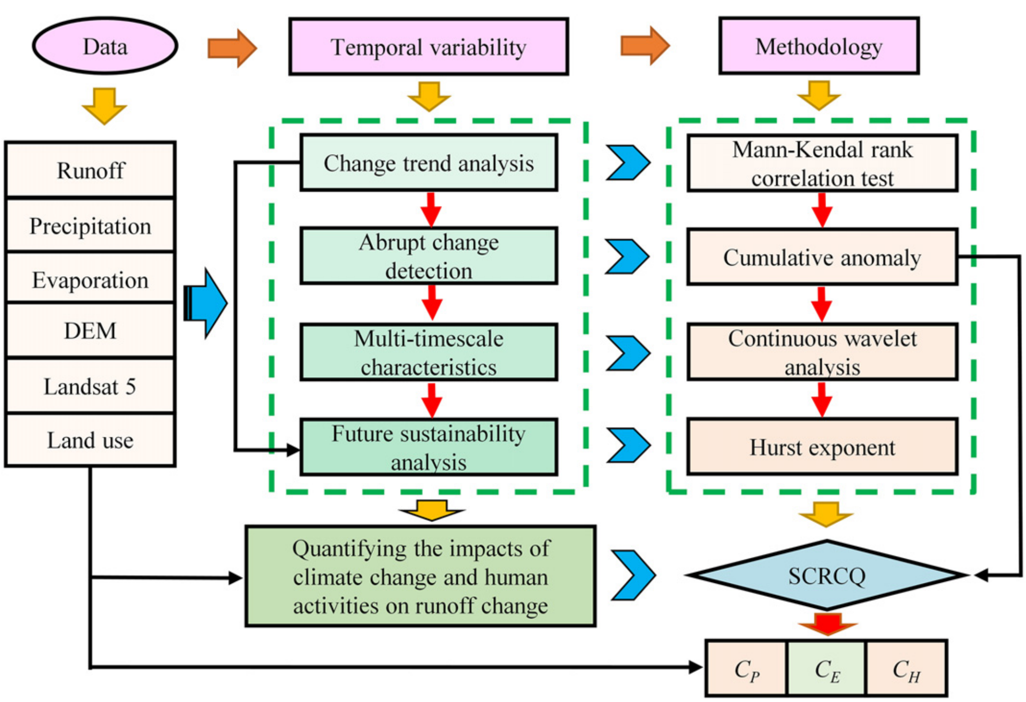

Fig. 3. Flowchart for technology system of quantifying the impacts of climate change and human activities on runoff change.

In addition, significant trends can explain the change in long-term time series. Theil-Sen median trend (Sen, 1968) is calculated by.

$$TS = \text{Median}\left(\frac{X_k - X_j}{k - j}\right) \qquad \forall j<k \tag{4}$$

where x_i and x_j represent the time series values of years i and j, respectively. In case of TS > 0, the time series presents an increasing trend; otherwise, it shows a decreasing trend.

To make the calculation results more concise and clear, the time series is standardized before Mann-Kendall rank correlation trend test analysis. The standardization of the formula is shown as follows (Wu and Huang, 2015):

$$X' = \frac{X - \text{mean}(X)}{\text{std}(X)} \tag{5}$$

where X is the original series, mean (X) is the mean of the series, and std (X) is the standard deviation of the series.

3.2. Cumulative anomaly

Cumulative anomaly is commonly used to identify the variation of hydrological and meteorological factors, such as sequential precipitation, evaporation, and runoff (Ran et al., 2010). For a discrete series x_i, the cumulative anomaly (S_t) for hydrological and meteorological data point x_i can be expressed as follows:

$$S_t = \sum_{i=1}^{t}(x_i - X_m) \tag{6}$$

$$X_m = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{7}$$

where X_m is the mean value of the discrete point series x_i, and n is the number of discrete points (Wang et al., 2012a).

3.3. Continuous wavelet analysis

Continuous wavelet analysis based on the Morlet function (Morlet et al., 1982; Christopher and Webster, 1998) has been widely used to identify periodic oscillations of signals (Labat, 2005; Werner, 2008). In recent years, continuous wavelet analysis has been applied to the analysis of multi-timescale features of hydrological and meteorological research. This method can clearly reveal a variety of changes in the time series and fully reflect the change trend of hydrological and meteorological data in different timescales.

Considering the series X_n as a continuous time series with t ranging from $-\infty$ to $+\infty$, then the Morlet function is chosen as the mother wavelet function to detect local temporal patterns of hydrological and meteorological data in this study, and is given (Zhang et al., 2016) as:

$$\Phi(t) = \pi^{-1/4 e^{ict}} e^{-t^2/2} \tag{8}$$

where $\Phi(t)$ is the Morlet wavelet function; i is the imaginary symbol of a complex number; c is the non-dimensional frequency, here taken to be 6 to satisfy the admissibility condition (Christopher and Webster, 1998); and t is time.

For a time series X_n, with $t = 0 \ldots n$, then the wavelet variance can be calculated by

$$W_n(a,b) = \left|a^{-\frac{1}{2}}\right| \int_{-\infty}^{\infty} X(t)\Phi^*\left(\frac{t-b}{a}\right)dt \tag{9}$$

$$\text{Var}(a) = \int_{-\infty}^{\infty}\left\{W_n(a,b)^2\right\}db \tag{10}$$

where W_n (a, b) is the wavelet transform coefficient and can present the characteristics of the signal change at different timescales; Var(a) is wavelet variance; $\Phi^*(t)$ is the complex conjugate of $\Phi(t)$; a is called a scaling parameter, which measures the degree of compression or scale; and b is the time shift or translation parameter which determines the time location of the wavelet (Zhang et al., 2016).

3.4. Hurst exponent

The rescaled range (R/S) analysis, proposed by the British hydrologist Harold Edwin Hurst (1951), explores trends in the time scale to study natural and socio-economic phenomena of non-linear quantity and the prediction method. Mandelbrot and Wallis (1969) improved this theory, which has been widely used in the fields of hydrology, climatology, economics, geology, and geochemistry. It has also been applied in detecting the time series of vegetation changes.

The basic principle of the R/S analysis is as follows. Defined a time series ξ_t ($t = 1, 2, \ldots, n$), divide the time series into t subseries of ξ_t, and the time span of the time series is defined as follows:

$$\tau = t_n - t_1 \tag{11}$$

(1) To calculate the difference of time series.

$$\xi_i = \xi_n - \xi_1 \tag{12}$$

(2) To calculate the mean series of the difference of time series.

$$\overline{\xi_i} = \frac{1}{t}\sum_{i=1}^{t}\xi_i \tag{13}$$

(3) To calculate the accumulated deviation.

$$X(t_i, n) = \sum_{i=1}^{t}\left(\xi_i - \overline{\xi_i}\right) \tag{14}$$

(4) To build the range series.

$$R(t_n - t_1) = R(\tau) = \max X(t,n) - \min X(t,n) \tag{15}$$

(5) To build the standard deviation series.

$$S(\tau) = \left[\frac{1}{t}\sum_{i=1}^{n}\left(\xi_i - \overline{\xi_i}\right)^2\right]^{\frac{1}{2}} \tag{16}$$

(6) Introducing the dimensionless ratio into rescale, obtains

$$\frac{R(\tau)}{S(\tau)} \propto \left(\frac{\tau}{2}\right)^H \tag{17}$$

where $\tau = 1, 2, ..., n$, ratio $R(\tau)/S(\tau) \propto (\tau/2)^H$ then a Hurst phenomenon exists in the time series of runoff, precipitation and evaporation. H is the Hurst exponent. The Hurst exponent reveals trend components of the time series and shows the intensity of the trend components. Three kinds of conditions exist for different H ($0 < H < 1$). First, when $H = 0.5$, the time series is a stochastic series without sustainability. Second, when $H > 0.5$, the sustainability of the time series exhibits the same trend as the time series in the future. Third, when $H < 0.5$, the anti-sustainability of the time series occurs.

The grading intensity table (Table 1) of the Hurst exponent is raised here to quantitatively describe the intensity of future trend components. The grading intensity of the Hurst exponent is divided into five grades from weak to very strong (Fan et al., 2008).

The statistic value $V_{(\tau)}$ is introduced to quantitatively describe the mean cycle of the future change trend of time series. The formula is as follows:

$$V_{(\tau)} = \left[\frac{R(\tau)}{S(\tau)}\right]_{\tau} / \sqrt{\tau} \tag{18}$$

$V_{(\tau)}$ can test the stability of R/S analysis, determine whether a time series has a periodical cycle, and estimate the cycle length. The statistic amount $V_{(\tau)} - \lg^{\tau}$ is close to flat for a series of independent random processes. The $V_{(\tau)} - \lg^{\tau}$ curve is upsweep for time series with inverse state persistence ($H > 0.5$). By contrast, $V_{(\tau)} - \lg^{\tau}$ curve is downward sloping for time series with inverse state persistence ($H < 0.5$). If $V_{(\tau)}$ in the $V_{(\tau)} - \lg^{\tau}$ curve is changed with the changing trend of $\lg^{\tau}$, that is, when the curve shows a significant turning point, the influence of the history state on the future state will disappear. The mean cycle of the system T is the corresponding time span τ. T refers to the mean memory length of initial conditions by the system, that is how long before the system loses its dependence on the initial condition completely and represents the length of persistent time in the future.

3.5. SCRCQ

The SCRCQ method was revised from the slope change ratio of accumulative quantity (SCRAQ) proposed by Wang et al. (2012b) to account for the contributions of influence factors to runoff change in different periods. The influence factors on runoff change in the Yinjiang River watershed generally include climate factors, groundwater recharge and human activities (Wang et al., 2012a).

Assuming that the slope of the linear relationship between year and cumulative runoff before and after a turning year is S_{Ra} and S_{Rb} (10^8 m^3/year), respectively, the slope of the linear relationship between year and cumulative precipitation before and after a turning year is S_{Pa} and S_{Pb} (mm/year), respectively, and the slope of the linear relationship between year and cumulative evaporation before and after a turning year is S_{Ea} and S_{Eb} (mm/year), respectively. The steps to calculate the contributions of climate change and human activities to runoff change are defined as follows:

(1) To calculate the change ratio of runoff (R_{SR} (%)), precipitation (R_{SP} (%)), and evaporation (R_{SE} (%)).

$$R_{SR} = \frac{S_{Rb} - S_{Ra}}{|S_{Ra}|} \tag{19}$$

$$R_{SP} = \frac{S_{Pb} - S_{Pa}}{|S_{Pa}|} \tag{20}$$

$$R_{SE} = \frac{S_{Eb} - S_{Ea}}{|S_{Ea}|} \tag{21}$$

(2) To calculate the contribution of the precipitation (C_P, unit: %), evaporation (C_E, unit: %) to runoff change after the turning year comparing to that before the turning year.

$$C_P = 100 \times \frac{R_{SP}}{R_{SR}} = 100 \times \frac{\frac{S_{Pb} - S_{Pa}}{|S_{Pa}|}}{\frac{S_{Rb} - S_{Ra}}{|S_{Ra}|}} \tag{22}$$

$$C_E = -100 \times \frac{R_{SE}}{R_{SR}} = 100 \times \frac{\frac{S_{Eb} - S_{Ea}}{|S_{Ea}|}}{\frac{S_{Rb} - S_{Ra}}{|S_{Ra}|}} \tag{23}$$

(3) To calculate the contribution of human activities (C_H, unit: %) to the runoff change based on water balance,

$$C_H = 100 - C_P - C_E - C_G \tag{24}$$

where C_G is the contribution of groundwater to the runoff change.

The groundwater recharge does not remarkably influence the annual runoff change because of distinct dry season (from Nov. to May) and wet season (from Jun. to Oct.) within a year according to previous studies (Wang et al., 2012a). Since the groundwater mainly affects the distribution of runoff in the year, the impact on the inter annual scale is negligible (Wang et al., 2015) and which also can be considered as part of human activities. So, the C_G in the Eq. (24) can be regarded as 0 for the Yinjiang River watershed in this study.

4. Results

4.1. The change characteristics analysis between runoff, precipitation, and evaporation

4.1.1. Inter-annual change characteristics

As shown in Fig. 4, the highest values of annual runoff was 7.64×10^8 m^3 in 2014, and the lowest was 2.91×10^8 m^3 in 2015. The maximum precipitation and evaporation values were 1435 mm in 2014 and 920.20 mm in 1985, respectively. The minimum precipitation and evaporation values were 718.90 mm in 2013 and 568.10 mm in 2014, respectively. Runoff and precipitation have similar inter-annual fluctuation patterns, and that evaporation has inverse characteristics with runoff and precipitation. The change in precipitation affected runoff change, and these two parameters were well synchronized.

Table 2 shows that the Z values of runoff, precipitation, and evaporation were 0.16, 0.45, and −2.14, respectively, according to Mann-Kendall rank correlation trend test. TS values were 0.01, 1.50, and −2.91, respectively. The Z value of evaporation passed the 0.05 significance test. This result indicated that runoff and precipitation showed a non-significant increasing trend, whereas evaporation showed a significant declining trend.

Table 1
Classification of Hurst exponent.

Grade	H		Strength
	Positive correlation	Negative correlation	
I	0.50 < H ≤ 0.55	0.45 < H ≤ 0.55	Weak
II	0.55 < H ≤ 0.65	0.35 < H ≤ 0.45	Weaker
III	0.65 < H ≤ 0.75	0.25 < H ≤ 0.35	Stronger
IV	0.75 < H ≤ 0.85	0.15 < H ≤ 0.25	Strong
V	0.85 < H ≤ 1.00	0.00 < H ≤ 0.15	Very strong

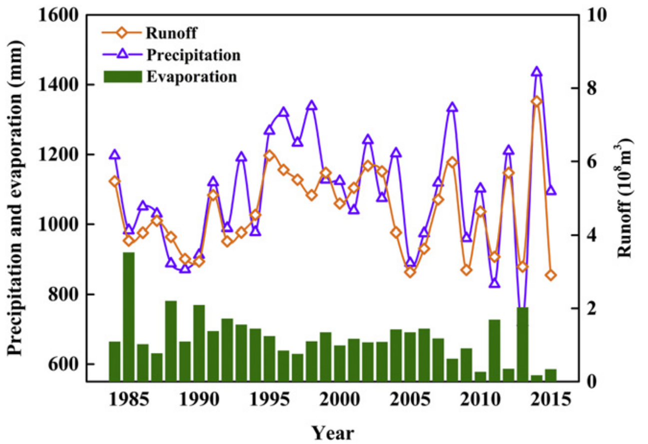

Fig. 4. The characteristics of inter-annual variation of runoff, precipitation, and evaporation.

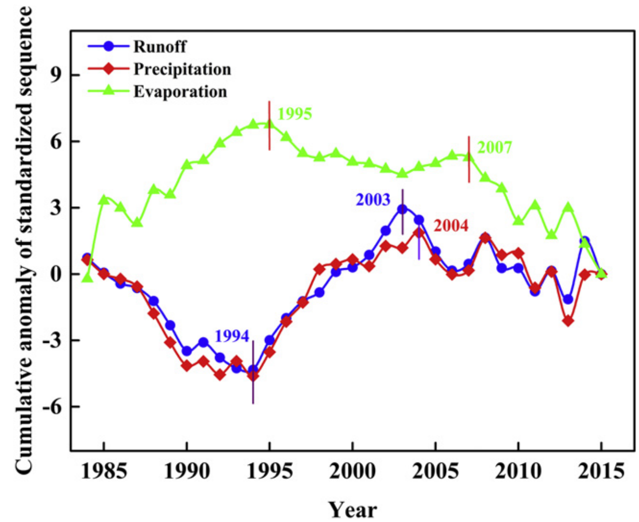

Fig. 5. The cumulative anomaly of runoff (a), precipitation (b), and evaporation(c).

4.1.2. Abrupt change characteristics

The changing characteristics of the cumulative anomaly curves of the runoff, precipitation, and evaporation of the Yinjiang River watershed over 1984–2015 are as shown in Fig. 5. The cumulative anomaly curve of runoff reached the lowest value in 1994 and the highest value in 2003, which were the maximum and minimum points of runoff, respectively. Runoff has a decreasing trend and an increasing trend before and after 1994, respectively, and then a decreasing trend after 2003. Therefore, the significant inflexion points of runoff were apparently 1994 and 2003 during the whole 32 years.

The cumulative anomaly curves shown in Fig. 5 indicated that precipitation has two significant inflexion points in 1994 and 2004 and that evaporation has two significant inflexion points in 1995 and 2007. Runoff and precipitation exhibited similar abrupt change features and stage characteristics. Moreover, runoff and precipitation both abruptly changed in 1994. Evaporation had an increasing stage before 1995 and exhibited characteristics that oppose those of runoff during this period. Evaporation then underwent a declining stage after 2007 and exhibited the same stage characteristics as runoff during this time. Thus, the abrupt change times of evaporation lagged 1–2 year(s) behind those of runoff and precipitation as a whole.

4.1.3. Multi-timescale characteristics

4.1.3.1. Inter-annual periodicity. The real part contour graphs and modular square diagrams (Fig. 6) of the wavelet coefficient of standardized runoff, precipitation, and evaporation were produced by continuous wavelet analysis. The results showed that the runoff time series had strong multi-timescale characteristics with oscillations of 3 years in 5–10-year timescale and 8 years in 18–26-year timescale (Fig. 6a). Energy signal was relatively strong (Fig. 6b) with the most significant periodicity that almost occupied the whole research time domain in 18–26-year timescale, and was relatively weak with locally significant periodicity in 5–10-year timescale. Periodicity was weak in the 1980s and strengthened after 1998. Three high centers and two low centers existed in the whole time domain in 18–26-year timescale and corresponded to 1984, 1999, and 2015, and 1992 and 2007. The periods of 1984–1988, 1995–2003, and 2011–2015 showed positive phases with high runoff. By contrast, the periods of 1989–1994 and 2004–2010 showed the negative phases with low runoff. Three high centers and three low centers occurred in 5–10-year timescale and corresponded to 2003, 2009, and 2015, and 2000, 2006, and 2012. The alternating cycles of positive and negative phases decreased. However, their frequencies were more detailed. Periodic change characteristics were dominated by the dry–wet alternating change of runoff and its multi-timescale features, further complicating changes.

Table 2
Mann-Kendall rank correlation trend test of runoff (Q), precipitation (P), and evaporation (E) in the Yinjiang River watershed from 1984 to 2015.

Name	Z	TS	Trend
Q (10^8 m^3)	0.16	0.01	+
P (mm)	0.45	1.50	+
E (mm)	−2.14*	−2.91	−

Notes: The Z index is a standardized Mann-Kendall rank correlation trend test to denote the positive (+) or negative (−) trend. TS is the significant trends of the time series. * Represents significance at $\alpha = 0.05$. The trend significance is distinguished by judging whether the absolute of Z value is >1.64 with a 95% statistical confidence level and 2.32 with a 99% statistical confidence level or not.

Fig. 6c shows that the precipitation time series had timescale periodic characteristics that were consistent with that for runoff. The high or low centers and positive or negative phases of precipitation tended to be close to that of runoff, however, their energy signal intensities were different (Fig. 6d). For precipitation, the high-intensity energy signals in 15–26-year timescale were mainly distributed before the 1990s. Therefore, the periodic characteristics in the 1980s were strong in this timescale. Moreover, high-intensity energy signals were distributed after 2000 in 5–10-year timescale with a markedly strengthening trend. Thus, the periodic characteristics of precipitation in this timescale were considerably enhanced and those of evaporation were considerably reduced (Fig. 6e). The multi-timescale characteristics of precipitation were dominated by the periodic characteristics in a small timescale. High or low centers and positive or negative phases of evaporation showed reverse correspondence to those of runoff and precipitation. Energy signal intensity was significantly different in 5–15-year timescale (Fig. 6f). Energy signal intensity in the 1980s and from 2010 to 2015 was strong with a weak intermediate period. Therefore, precipitation and runoff had similar multi-timescale characteristics with strong periodic characteristics in a large timescale. The multi-timescale characteristics of evaporation showed an inverse correspondence with that of runoff, which was mainly reflected in a small timescale.

4.1.3.2. Main influence periods of runoff, precipitation and evaporation. In the present study, wavelet variance analysis was utilized to quantitatively analyze the changes in the abundant–low characteristics and periodic intensity of runoff, precipitation, and evaporation over different main periods. As shown in Fig. 7, the wavelet variance graph for runoff had three significant peaks of 3-year, 10-year, and 23-year timescales from small to large. The maximum peak of the 23-year timescale was

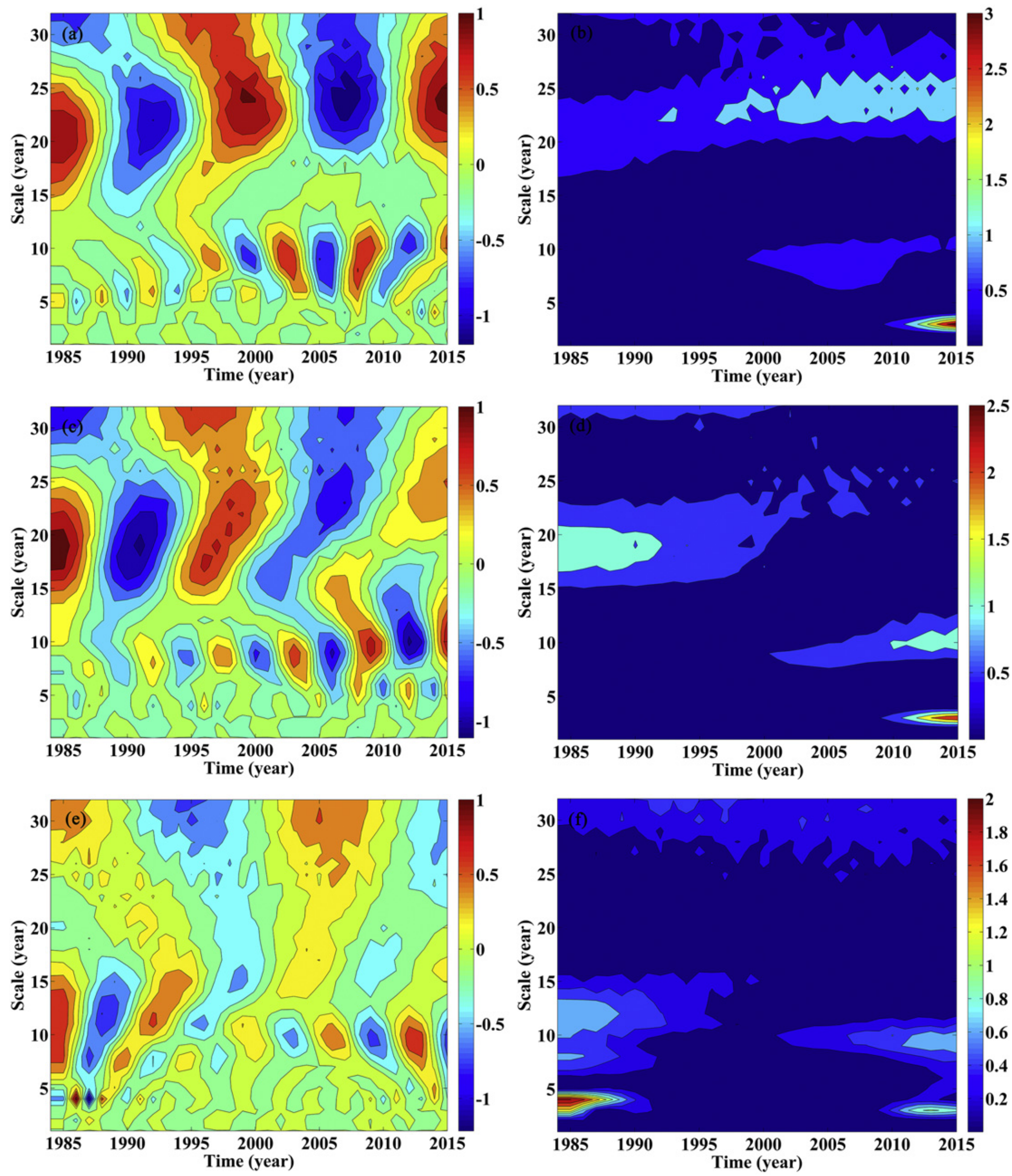

Fig. 6. The time-frequency distribution of Morlet wavelet transform coefficients real part contour graphs and the modulus square diagrams of the standardized runoff (a, b), precipitation (c, d), and evaporation (e, f).

the first main period for the periodic change of runoff, and 3-year and 10-year timescales were the second and third main periods, respectively. Precipitation had the first, second, and third main periods of 20-year, 3-year, and 10-year timescales, respectively. Furthermore, two apparent peaks existed in 10-year and 4-year timescales in the whole time domain for evaporation, namely, the first and third main periods, and a local peak in 32-year timescale was the second main period. These results showed that the periodic changing characteristics of runoff were similar to those of precipitation.

4.1.3.3. Abundant-low transit characteristics in different main periods. In this study, the mean period and abundant-low transit characteristics of runoff, precipitation, and evaporation were analyzed based on different main period timescales. Fig. 8 shows that runoff and precipitation had more consistent abundant-low transit characteristics in the three timescales of the main periods. The mean periods in 20-year and 23-year timescales were approximately 16 years with two abundant-low transit periods. Runoff, precipitation, and evaporation exhibited consistent abundant-low transit characteristics with a transformation period of 7 years in 9-year and 10-year timescales, with five periods of abundant-low transformation. The abundant-low transit characteristic of evaporation in 4-year timescale was consistent with those of runoff and precipitation in 3-year timescale with a mean changing period of 2 years. The abundant-low transit characteristics of runoff and precipitation were significant in a large timescale, whereas those of evaporation were reversed. Runoff, precipitation, and evaporation had more consistent abundant-low transit characteristics in a small time scale and significantly features in 9-year and 10-year timescales. Those characteristics, however, were only significant at the end of periods in 3-year and 4-year timescales and without significant features in the middle of periods in these timescales.

4.1.4. Long-term memory characteristics and future trends

The Hurst exponent was used to analyze the persistent characteristics of runoff, precipitation, and evaporation time series and then to generate the fitting curves of $R_{(\tau)}/S_{(\tau)} - \tau$ and $V_{(\tau)} - \lg^{\tau}$ (Fig. 9). As shown

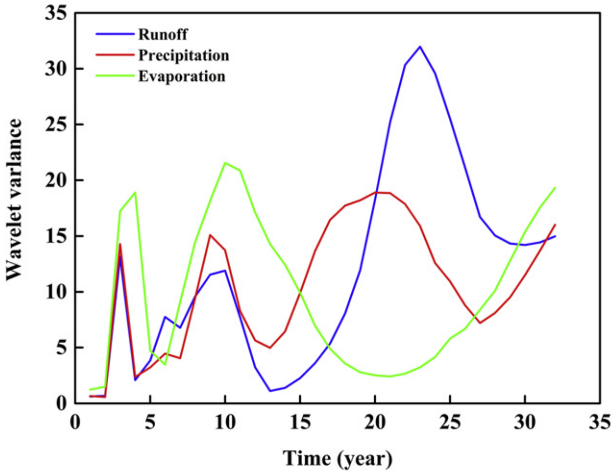

Fig. 7. The wavelet variance curves of the standardized runoff, precipitation, and evaporation.

in Table 3, the H values of runoff, precipitation, and evaporation time series were 0.38, 0.35, and 0.36 ($H < 0.5$), respectively. This finding indicated that the future trends of runoff, precipitation, and evaporation opposed those of the past. Thus, in the future, runoff and precipitation will decrease, whereas evaporation will continuously increase. According to the classification of H values with persistent strength in Table 1, the continuous intensity of runoff, precipitation, and evaporation were the classification of weaker persistence with Grade II persistent strength. The persistent times of T for runoff, precipitation, and evaporation were 21 years, 17 years, and 26 years, respectively. Furthermore, evaporation had the maximum H value and the longest persistent time, whereas precipitation had the minimum H value and the shortest persistent time. Thus, precipitation will continuously decrease, whereas evaporation will continuously increase in the next 21 years or so, and the continuous decline of runoff might trigger a serious water shortage crisis.

4.2. Quantifying the impacts of climate change and human activities on runoff change

The research shows an inconsistent relationship for abrupt change year between climatic factors and runoff. Thus, to thoroughly analyze the influence of climatic factors on the runoff of the Yinjiang River watershed, this study divided precipitation and evaporation time series into periods of Ta (1984–1994), Tb (1995–2003), and Tc (2004–2015) based on the year that exhibited abrupt changes in runoff. Periods of Ta (1984–1994), Tb (1995–2003), and Tc (2004–2015) were designated as the base, abrupt change, and measure periods, respectively. Correlation formulas were fitted (Fig. 10) between year and accumulation of runoff, precipitation, and evaporation, respectively. The correlation coefficient of R values fitted between year and each factor was high and exceeded 0.99. Meanwhile, the confidence level of P values was <0.0001. Thus, the correlation between each factor and years was high. To quantitatively separate the influences of precipitation, evaporation, and human activities on runoff change, the first period Ta (1984–1994) was considered as the stage during which the climatic factors played a controlling role. Human activities in this interval were relatively weak. Since the mid-1980s, however, human activities have become more frequent. In addition, various water and soil conservation activities have been developed rapidly during this interval. Thus, climatic factors and human activities have exerted more control on runoff change since the mid-1980s.

As shown in Table 4, the slope S_R of the relation between year and cumulative runoff during period Ta (1984–1994), Tb (1995–2003), and Tc (2004–2015) were 3.99×10^8, 5.40×10^8, and 4.46×10^8 m^3/year, respectively. Compared with runoff during period Ta (1984–1994), that during period Tb (1995–2003) increased by

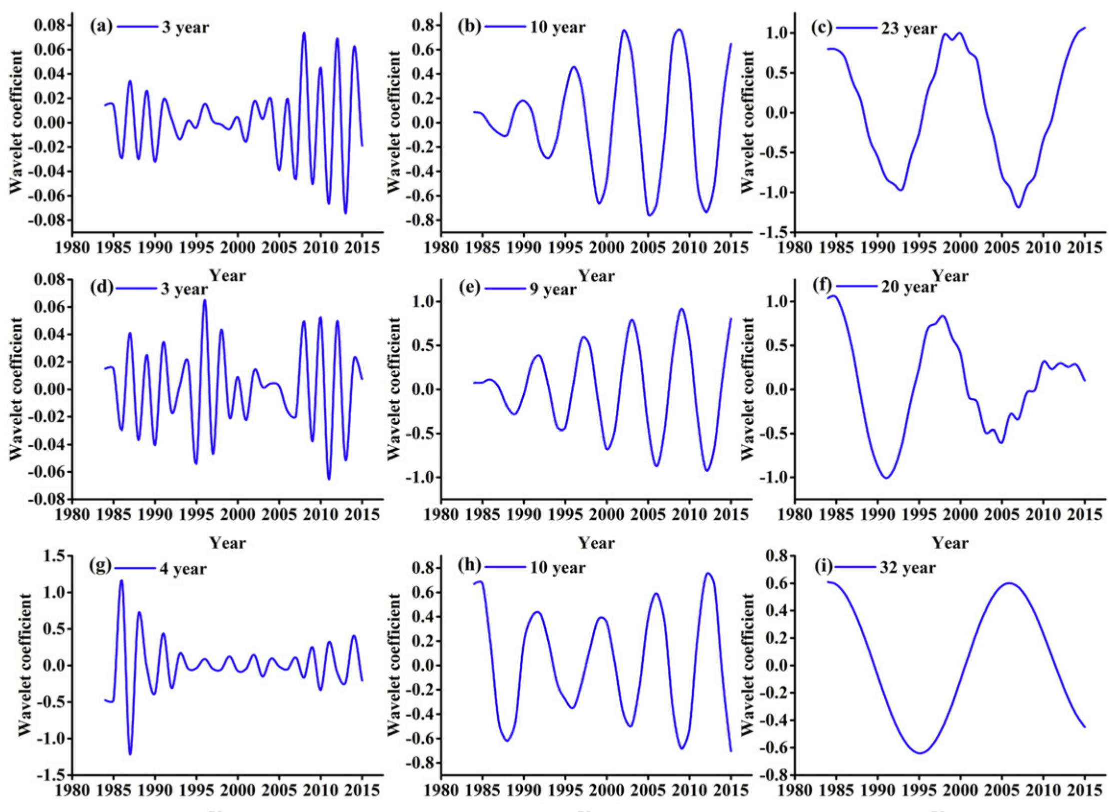

Fig. 8. The wavelet coefficients real part curves of different main periods of the standardized runoff (a, b, c), precipitation (d, e, f), and evaporation (g, h, i).

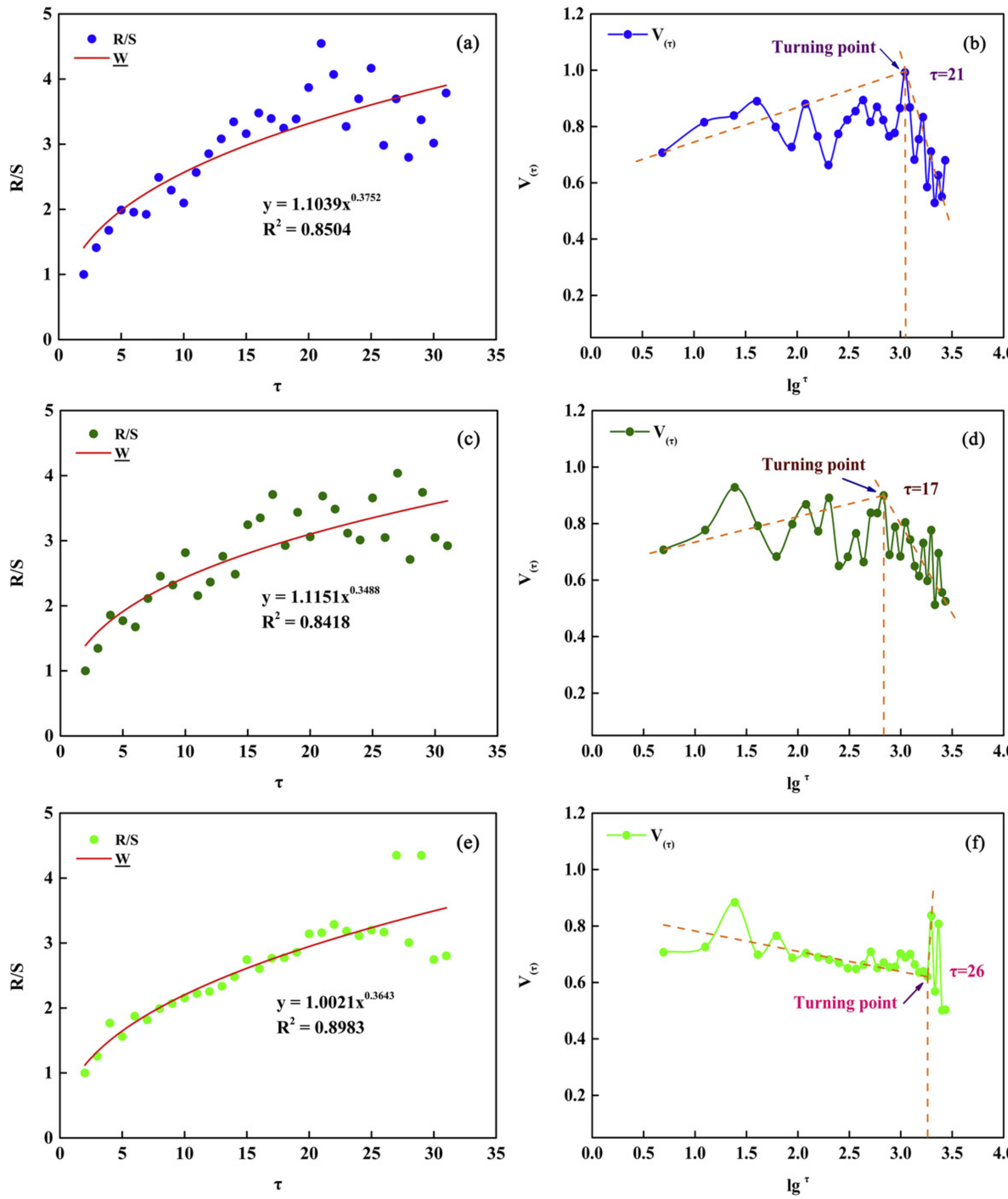

Fig. 9. Fitting curves for the result of Hurst exponent analysis and the persistent times of runoff (a, b), precipitation (c, d), and evaporation (e, f).

Table 3
Results of Hurst exponent analysis and the future sustainability features of runoff (Q), precipitation (P), and evaporation (E).

Name	R^2	H	T	Change trend	
				Historical	Future
Q (10^8 m^3)	0.85	0.38	21	+	−
P (mm)	0.84	0.35	17	+	−
E (mm)	0.90	0.36	26	−	+

Notes: R^2 is the goodness of fit with $R_{(\tau)}/S_{(\tau)}$ and time lag τ. H is the Hurst exponent and T is the persistent times of runoff, precipitation, and evaporation, respectively. "+" represents an increasing trend and "−" is s decreasing trend in this table.

35.33%, and that during period Tc (2004–2015) increased by 11.78%. Compared with runoff during period Tb (1995–2003), that during period Tc (2004–2015) decreased by 17.41%.

As shown in Table 5, taking period Ta (1984–1994) as the base period, the contributions of precipitation, evaporation, and human activities to runoff change were 53.92%, 21.61%, and 24.47% during period Tb (1995–2003), respectively, and were 59.59%, 80.94%, and −40.53% during period Tc (2004–2015), respectively. Ignoring the effects of evaporation, the contributions of human activities to runoff change were 46.08% during period Tb (1995–2003) and 40.41% during period Tc (2004–2015). Thus, taking period Ta (1984–1994) as the base period, the contributions of precipitation, evaporation, and human activities to runoff change were all slightly enhanced. In addition, the proportion of impacts of climatic factors on runoff change increased from 75.53% to

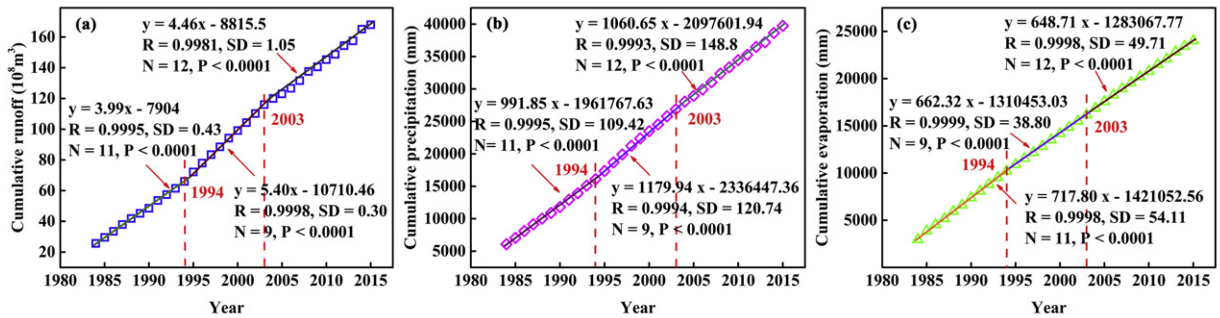

Fig. 10. The relations between year and accumulation of runoff (a), precipitation (b), and evaporation (c).

140.53% and those of human activities changed from 24.47% to −40.53%. Thus, taking period Ta (1984–1994) as the base period, climate change on runoff change was the dominant factor and showed an increasing trend.

Taking the period Tb (1995–2003) as the base period, the contributions of precipitation, evaporation, and human activities to runoff change during period Tc (2004–2015) were 58.08%, −11.80%, and 53.73%, respectively. Ignoring the effects of evaporation, the contribution of human activities to runoff change was 41.92%. The proportions of impacts of climatic factors and human activities on runoff change were 46.27% and 53.73%, respectively.

Since 1984, precipitation has strongly influenced runoff change in the whole period with a stable state and high contribution of 50%–60%. By contrast, the impacts of evaporation on runoff change have changed markedly with a positive or negative effect of 10%–90%. In addition, the impacts of human activities on runoff change have gradually strengthened and have gradually changed from enhancement to attenuation, maintaining a lower positive or negative effect of 20%–50%. The contribution of climatic factors to runoff change showed a great difference because of the difference of the base periods. When accounting for the effects of evaporation, the contributions of human activities to runoff change gradually increased but remained relatively stable (40%–50%) without considering the effects during different periods.

5. Discussions

5.1. Comparison of the SCRCQ results with that in non-karst watershed

SCRCQ was first proposed in 2012 and had been applied in the investigation of Huangfuchuan River basin of the Yellow River basin in China (Wang et al., 2012b). In recent years, SCRCQ has been widely used in the basins of Songhua River (Wang et al., 2015), Liao River (Ma et al., 2015), and Hei River (K.S. Luo et al., 2016). Given regional differences, most of the results of previous studies were slightly different from those of the present study. For example, a study on the whole Yellow River basin by Wang et al. (2012a) revealed that when the effect of evaporation was ignored, the contributions of precipitation and human activities to runoff decrease in Huangfuchuan River basin during the abrupt change period were 36.43% and 63.57% respectively and were 16.81% and 83.19% during the measure period, respectively. A study on the middle reaches of the Yellow River basin reported that when the effect of evaporation was ignored, the contributions of precipitation, evaporation, and human activities to runoff change were 25.94%, −17.68%, and 74.06%, respectively, in the abrupt change period, and were 25.13%, −18.54%, and 74.87%, respectively, in the measure period. When the effect of evaporation is considered, the contributions of human activities to runoff change in the middle reaches of the Yellow River basin increased to 91.74% and 93.41% during the abrupt change and measure periods respectively (Wang et al., 2013). For the entire Yellow River basin, the contributions of precipitation and evaporation to runoff change in the measure period were 11.76% and −3.83%, respectively. The contribution of human activities to runoff change was 92.07% when the effect of evaporation was ignored and was 88.24% (Wang et al., 2012a) when the effect of evaporation was considered. Moreover, it was found that the contribution of climatic factors to runoff change was approximately 40%–60% in the basins of Songhua River (Wang et al., 2015), Hei River (He et al., 2012), Wei River (Huang et al., 2016b), and Huangshui River (Zhang et al., 2014). In addition, the contribution of precipitation to runoff change was approximately 30%, and that of evaporation to runoff change was generally 20% or less and even lower than 10% in most watersheds. In some watersheds, the effect of evaporation on runoff change was approximately 10% of that of precipitation (Meng and Mo, 2012), with only 3% in some other watersheds (Wang et al., 2015). Human activities most strongly influence runoff change in a non-karst watershed, with a contribution of 70%–100%, and the contribution of climatic factors is <50%.

The results of this study showed that the contributions of precipitation, evaporation, and human activities to runoff change in the Yinjiang River watershed were in a steady state of 50%–60%, in a positive or negative effect of 10%–90%, and in a lower positive or negative effect of 20%–50%, respectively. The contribution of precipitation to runoff change was in a relatively stable state. By contrast, the contributions of evaporation and human activities to runoff change were significantly different and had an enhanced trend with period Ta (1984–1994) as the base period. Taking period Ta (1984–1994) as a base period, climatic factor was identified as the dominant factor, and its effects and those of human activities on runoff change were significantly enhanced. However, taking period Tb (1995–2003) as a base period, human activities

Table 4
The slopes of the relations between year and cumulative quantities of runoff (S_R), precipitation (S_P), and evaporation (S_E).

Slope	Ta	Tb	Tc
S_R (10^8 m^3/year)	3.99	5.40	4.46
S_P (mm/year)	991.09	1179.94	1060.65
S_E (mm/year)	717.08	662.32	648.71

Notes: Periods of Ta, Tb, and Tc represent the periods of 1984–1994, 1995–2003, and 2004–2015, respectively.

Table 5
The contributions of climate change and human activities to runoff changes in study area.

Impact factor	Contribution to the runoff changes (%)		
	Based on (Ta)		Based on (Tb)
	Tb	Tc	Tc
C_P	53.92	59.59	58.08
C_E	21.61	80.94	−11.8
C_H	24.47	−40.53	53.7
$C_P + C_E$	75.53	140.53	46.27
$C_E + C_H$	46.08	40.41	41.92

Notes: Periods of Ta, Tb, and Tc represent the periods of 1984–1994, 1995–2003, and 2004–2015, respectively. C_P, C_E, and C_H represent the contributions of precipitation, evaporation, and human activities to runoff changes, respectively. $C_P + C_E$ represent the contribution of climate change to runoff changes, and $C_E + C_H$ represent the contribution of human activities to runoff changes without considering the effects of evaporation.

played the most important role in runoff change except for precipitation. Given the complexity of the environmental background and the differences in human activities among all periods, the dominant factors that affect runoff change in the Yinjiang River watershed varied among different base periods. However, human activities were the dominant factor in non-karst watershed throughout the whole period in many areas. The main factors that affect runoff in the Yinjiang River watershed have changed because human activities have changed the route of part of water cycle in this region. In addition, the effect on runoff change was reflected in the actual evaporation change, thus changing the proportion of the influences of climatic factors and human activities on runoff change. Moreover, in climatic factors, the contributions of precipitation and evaporation in the Yinjiang River watershed were higher than those in non-karst watershed, and the effects of evaporation on all periods were significantly different. The main driving factors and their contributions regarding climate change and human activities to runoff change in the Yinjiang River watershed were significantly different from those in non-karst watershed. These differences may be caused by the spatial differences in climatic factors, the intensity of human activities, and the hydrological and geographical environmental between a karst watershed and a non-karst watershed.

5.2. Impacts of precipitation on runoff change

Taking period Ta (1984–1994) and period Tb (1995–2004) as the base periods, respectively, the contributions of precipitation to runoff change all increased by 5%–6% during period Tc (2004–2015). This increase was related to the implementation of numerous soil protective measures and water resources utilization projects on the slopes of the Yinjiang River watershed during period Tc (2004–2015). For example, numerous surface water resources utilization technologies (Qin et al., 2015) were implemented in rocky desertification control projects, including collection technologies for runoff water in the gully section. Other established technologies included road–channel–pool integrated road rainwater collection and water cellars that were designed for micro-relief or negative terrain. These technologies were used to intercept, collect, and store rainwater. The high amounts of rainfall were retained on the slope surface, thus hindering runoff formation. Therefore, the effect of precipitation on runoff change during period Tc (2004–2015) slightly increased. Moreover, precipitation and runoff had similar multi-timescale characteristics (Fig. 6). Hence, runoff change was affected by the periodic change in precipitation and the increasing contribution of precipitation to runoff change.

During all periods, the contributions of precipitation to runoff change in the Yinjiang River watershed were higher than those to runoff change in non-karst watershed and were maintained at a relatively higher level of 50%–60%. Negligible differences existed among all periods. Consistent with the results obtained in the present study, a study by Kong et al. (2007) indicated that in a karst area, the evolution of annual runoff was mainly affected by the natural factors of average annual precipitation. For example, runoff change was strongly affected by changes in precipitation. The double mass curve of runoff with precipitation (Fig. 11a) showed that runoff and precipitation were strongly correlated (R^2 of 0.9996). Moreover, the multi-timescale characteristics of precipitation had an important influence on runoff change. As shown in Fig. 8, runoff had a more consistent abundant-low transit characteristic with precipitation than that with evaporation during the three main periods, showing that precipitation was the main factor of runoff change.

In addition to the effect of multi-timescale characteristics, the contributions of precipitation to runoff change are also restricted by the hydrogeological structure and topographic features of the Yinjiang River watershed. In the study area, the lithology and hydrogeological structure are special and complex. With a typical dualistic 3-D hydrogeological structure (G.J. Luo et al., 2016), a typical landform exhibits a one-trough, two-ridge terrain feature with a synclinal structure and a low density of the river network due to the wide development of the karst. Thus, the area of runoff formation is greatly reduced. Given the development of surface rock cracks, fissures, and underground channels in karst mountain areas (Wang et al., 2004), the surface is broken, the soil layer is shallow, the soil permeability is high, the water-holding capacity is poor (Li et al., 2011; Chen et al., 2012; Peng and Wang, 2012), and the runoff coefficient of the slope is far lower than those in a non-karst watershed (Yan et al., 2000; Dong et al., 2009). Water loss is especially worsened by the numerous karst fissures and channels that have developed in the bedrock structure of the valleys. These fissures and channels are connected to the broken surface and provide conditions that facilitate surface water loss. Once the atmospheric precipitation reaches the ground, high amounts of rainfall rapidly pass through the developed underground channels and cracks into the underground rivers, which then flow into other watersheds through underground rivers or pipelines or are stored in an underground karst environment to gather in a surface channel. These features result in the poor storage capacity of the karst watershed and are the main reasons for high contribution of precipitation to runoff change.

The high contribution of precipitation to runoff change originates from the difficulty of runoff generation on a sloping surface after primary rainfall and the considerable influence of high runoff from gullies after secondary rainfall on runoff change. Based on analysis of different runoff plots in a karst mountainous area, high slope runoff will be generated from a single precipitation event that exceeds 60 mm (Peng et al., 2009). The mean monthly precipitation data for the Yinjiang River watershed indicated that each period had five months with <60 mm of precipitation (Fig. 12). Thus, the Yinjiang River watershed did not generate considerable surface runoff for nearly half a year. Runoff is produced by the higher precipitation and the greater impact of secondary

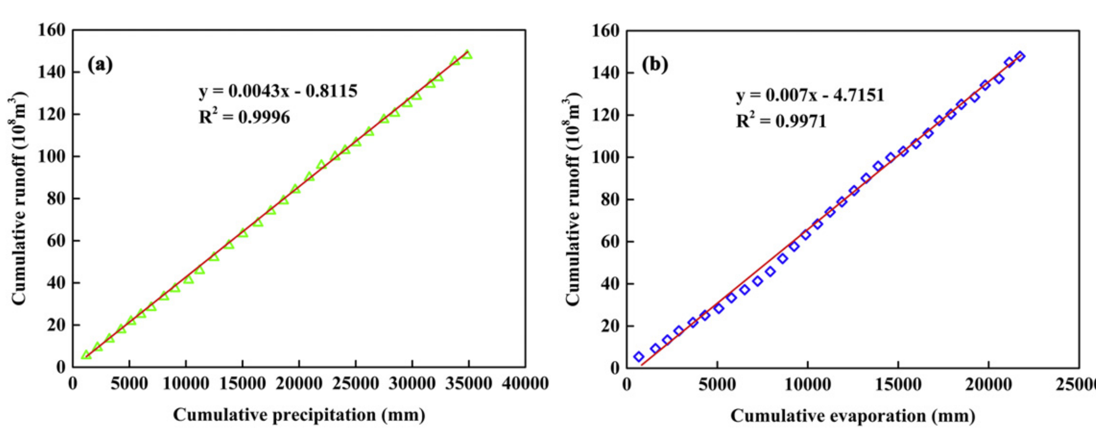

Fig. 11. Double mass curves for runoff and precipitation (a), and runoff and evaporation (b).

rainfall during the summer and autumn seasons. Moreover, the gully had a low groundwater level on a dolomite slope. The epikarst is immediately saturated after primary rainfall, and the surface runoff coefficient increase and easily causes runoffs after secondary rainfall in gullies, thus exerting a great impact on runoff change.

5.3. Impacts of evaporation on the runoff change

The fluctuation in the contribution of evaporation to runoff change was relatively different and showed an enhanced trend in the Yinjiang River watershed. Taking period Ta (1984–1994) as the base period, the contribution of evaporation to runoff change increased from 21.61% during period Tb (1995–2003) to 80.94% during period Tc (2004–2015). The effect of evaporation on runoff change was significantly enhanced in the Yinjiang River watershed, showing a greater contribution than that in non-karst watershed. Evaporation has a higher impact on runoff change because of the influence of the subtropical monsoon climate, abundant light, and heat resources in Southwest China. Furthermore, human activities, such as vegetation restoration and water conservation projects (Tian et al., 2017), have changed the underlying surface characteristics of the watershed. The construction of water conservancy projects has changed the natural characteristics of the spatial and temporal cycle of runoff, thus decreasing the evaporation and changing the water cycle in period Tc (2004–2015). Evaporation is strongly related to vegetation coverage, air temperature, and precipitation. Evaporation is positively correlated with rainfall and vegetation cover (Wang et al., 2012a). The land use maps of the Yinjiang River watershed (Fig. 13) showed that vegetation coverage in the region mainly consists of forest and pasture lands. Vegetation covered 640.34 km^2 in 1990, 435.28 km^2 in 2000, and 602.40 km^2 in 2010. The area covered by vegetation increased by 38.39% from 2000 to 2010 (Table 6). Precipitation showed no significantly increasing trend according to the result of Mann-Kendall rank correlation trend test from the Section 4.1.1. The continued increase in precipitation and vegetation coverage contributed to the continuously increasing trend of the high contribution of evaporation to runoff change with period Ta (1984–1994) as the base period. Their proportions in the changing process of precipitation and vegetation cover were different in different periods. Thus, the effect of evaporation on runoff change was different as well. As in shown in Fig. 11b, runoff was strongly correlated with evaporation (R^2 of 0.9971), showing that runoff change was strongly affected by the change in evaporation. Moreover, terrain features and temperature in the Yinjiang River watershed also increased the contribution of evaporation to runoff change. Surface water in the Yinjiang River watershed is mainly concentrated in the river. The lack of water on the land surface, high temperatures, and high-intensity evaporation greatly affected runoff loss. Furthermore, the effect of precipitation on runoff change was more stable throughout all periods, whereas the effect of evaporation was significantly different. The above factors significantly increased the contribution of evaporation to runoff change during period Tc (2004–2015).

5.4. Impacts of human activities on runoff change

The effect of human activities on runoff change in the Yinjiang River watershed was lower than that in a non-karst river watershed but showed an increasing trend. Taking period Ta (1984–1994) as the base period, the contributions of human activities to runoff change were 21.61% during period Ta (1984–1994) and −40.53% during period Tb (1995–2003). Without considering the effect of evaporation, the contributions of human activities to runoff change were 46.08% during period Ta (1984–1994) and 40.41% during period Tb (1995–2003), respectively. Taking period Tb (1995–2003) as the base period, the contribution of human activities to runoff change during period Tc (2004–2015) was 53.73% and was 41.92% without considering the effect of evaporation. Thus, the impact of human activities on runoff change is restricted by evaporation. Moreover, human activities interfered with runoff change, with increasingly stronger effects.

Results showed that taking period Ta (1984–1994) as the base period, the effect of climatic factors on runoff change exhibited a decreasing trend and that of human activities on runoff change gradually increased. The intensity change of human activities is mainly represented by the change in land use, which can affect the hydrological process (Woldesenbet et al., 2017). The land use maps of the Yinjiang River watershed showed that the change in the areas of slope farmland and construction reflected the change of the intensity of human activities during period Ta (1984–1994), Tb (1995–2003), and Tc (2004–2015). Paddy field and construction land were the main causes of runoff loss. As shown in Table 6, the areas of construction land and paddy field were 68.48 km^2 and 8.62 km^2 in 1990, 236.48 km^2 and 9.81 km^2 in 2000, and 176.32 km^2 and 20.70 km^2 in 2010. As shown in Table 7, the percentage of change rate for construction land and cultivated field were 245.31% and 13.70% from 1990 to 2000, 157.45% and 139.99% from 1990 to 2010, and −25.44% and 111.07% from 2000 to 2010. Other types of land use drastically and rapidly changed, thus indicating that the human activities during the three periods were intensive and rapid. Although construction land showed the trend of initially increasing and then decreasing, it increased by 245.31% in 2000 and 157.45% in 2010 compared with it in 1990. Meanwhile, paddy field showed a sustained growth trend, thus indicating that human activities increased the amount of water used from runoff. Therefore, the contributions of human activities to the runoff change had been an increasing trend. Period Ta (1984–1994) was the starting period after implementing the land contract responsibility system in the Yinjiang River watershed, and human activities started to increase this time. During period Tb (1994–2003), the destruction of the natural environment by human activities was the most intense and resulted in high amounts of soil and water loss. Runoff enhancement represented the effect of human activities. However, during period Tc (2004–2015), the implementation of rocky desertification projects enhanced water and soil retention on sloping surfaces. These projects achieved ecological restoration and eased the effect of water and soil loss. Abundant surface runoff is intercepted by transforming slopes into a terraces, planting

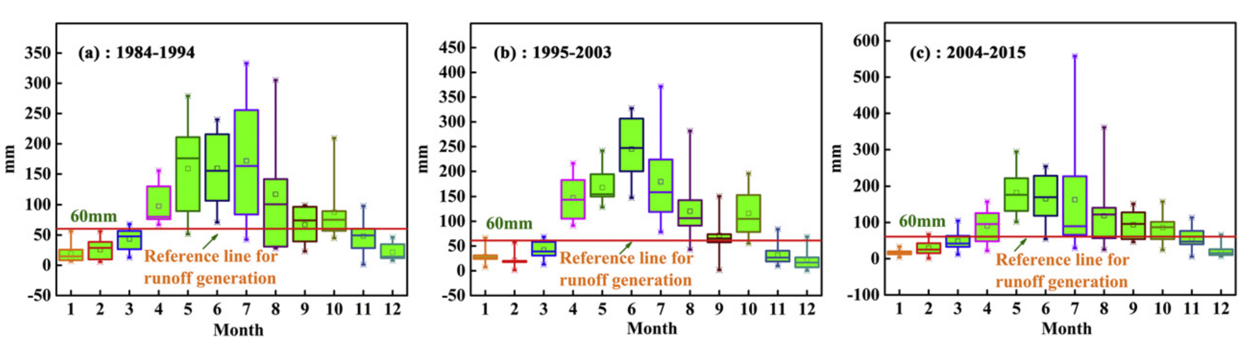

Fig. 12. Comparison of monthly average precipitation of the Yinjiang River watershed between 1984–1994 (a), 1995–2003 (b), and 2004–2015 (c). Box plots: the central mark is the median; the small square inside the box is the average; the box-edges are the 25th and 75th percentiles; and the whiskers extend to the1st and 99th percentiles.

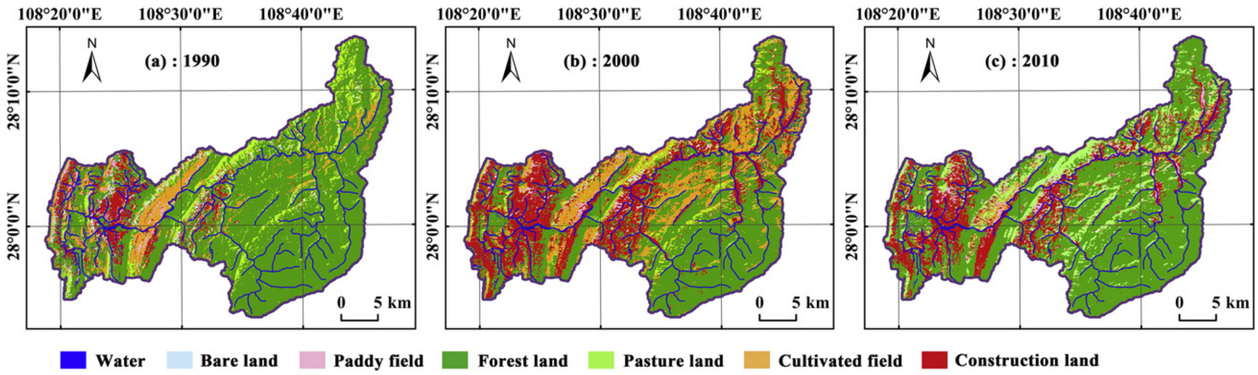

Fig. 13. Land use of the study area in 1990 (a), 2000 (b), and 2010 (c).

trees and grass, diversion irrigation, and other efforts. Moreover, water demand has increased with the continued population growth, rapid economic and urban development, and expanding industrial and mining enterprises, thereby increasing water consumption from runoff. Thus, the influence of human activities on runoff change in the Yinjiang River watershed decreased the slope runoff through intercepting–holding–leading–using on the slope surfaces of the region. Therefore, the effective catchment area for runoff convergence was greatly reduced, and the efficiency of flow concentration of river channels was decreased.

Previous studies have reported that the construction of reservoirs, dams, and inter-watershed water diversion projects to intercept and retain runoff are the main anthropogenic activities that influence runoff in non-karst watersheds (Xu et al., 2009; Wang et al., 2013; Zhao et al., 2014). Most of the intercepted and retained water enters atmospheric circulation via evaporation. However, the construction of reservoirs and dams in the Yinjiang River watershed is hindered by its typical karst terrain. Therefore, the lack of construction projects account for low contribution of human activities on runoff change in the Yinjiang River watershed. The influence of human activities on runoff change in the Yinjiang River watershed involved the development of rocky desertification control projects to manage water, conserve soil, and restore vegetation coverage on the karst surface and slopes. Moreover, economic development and population growth also increased the amount of water consumption, thus changing the route of water cycle. Thus, compared with the non-karst watershed with many dams and reservoirs that seriously influenced the runoff change, the effect of human activities on runoff change in the Yinjiang River watershed was relatively weak and its contribution was slightly lower.

5.5. Uncertainty of quantitative assessment

The uncertainty of quantitative assessment was mainly manifested in the following aspects. First, calculating the contribution of each measure to the runoff change in the Yinjiang River watershed was difficult because the data of each measurement and project for every year were not completely collected. In addition, several statistical data were incorrect, especially the water data of various human activities. Second, the decomposition of climatic factors and human activities was lack of thoroughness. Thus, the contributions of the specific human activities and each climatic factor was not be quantified. Furthermore, this study considered precipitation and evaporation only as climatic factors, which should actually include sunshine, temperature, wind speed, and other factors. Meanwhile, the effects of human activities have various aspects that are considered as non-natural factors. Therefore, this study simplified the climatic factors that affect runoff change into two major factors of precipitation and evaporation and attributes all non-natural factors to human activities. The comprehensive effects of a variety of specific human activities included the implementation of water and soil conservation projects. Thus, this study only explored the comprehensive, not specific, the effects of various human activities on runoff change. In addition, the influence of precipitation and evaporation on runoff change is not a purely natural effect. The change of the underlying surface by human activities have indirectly influenced the contributions of precipitation and evaporation to runoff change, indicating that the theoretical values of the contributions of human activities to runoff change were lower than the actual values.

5.6. Prospects for future research

The results of this study can be used to manage water resources in a karst watershed. Moreover, the SCRCQ method can be applied in quantitatively evaluate the impacts of different factors on runoff change in a karst watershed. However, given the influence of uncertain factors on methods and the limitations on hydrological data, future research should utilize hydrological models to recognize and effectively separate the detailed influence of climate change and human activities on runoff change. In addition, the contributions of other non-natural factors to runoff change should be calculated to determine the runoff yield of different land-use types. Then, the contribution of human activities to runoff change should be accurately calculated based on the balance of water yield and water consumption in a karst watershed. These ideas will be carried out in the next step of hydrological researches in the Yinjiang River watershed.

6. Conclusions

This study takes the Yinjiang River watershed as the research site, analyzes the change trend, abrupt change characteristic, multi-

Table 6
Land use area of the study area in 1990, 2000, and 2010.

Year	Area (km^2)						
	Bare land	Construction land	Cultivated field	Forest land	Paddy field	Pasture land	Water
1990	26.69	68.48	70.68	569.70	8.62	70.64	14.86
2000	8.63	236.48	128.53	392.80	9.81	42.48	10.96
2010	3.97	176.32	17.09	486.79	20.70	115.61	9.30

Table 7
Percentage of land use change rate of the study area based on 1990 and 2000.

Land use	Area change rate (%)		
	From 1990 to 2000	From 1990 to 2010	From 2000 to 2010
Bare land	−67.67	−85.12	−53.97
Construction land	245.31	157.45	−25.44
Cultivated field	81.85	−75.82	−86.70
Forest land	−31.05	−14.55	23.93
Paddy field	13.70	139.99	111.07
Pasture	−39.86	63.66	172.13
Water	−26.23	−37.45	−15.21

timescale characteristics between 1984 and 2015 based on Mann–Kendall rank correlation trend test method, cumulative anomaly, and continuous wavelet transform, calculates the contributions of climate change and human activities to runoff change by SCRCQ, and analyzes the long-term memory characteristics and future trends based on Hurst exponent. The main conclusions are as follows:

(1) From 1984 to 2015, runoff and precipitation exhibited no significant increasing trend, whereas evaporation exhibited significant decreasing trend. In the future, runoff, precipitation, and evaporation will exhibit weak anti-persistent feature with different persistent times of 21 years, 17 years, and 26 years, respectively. This feature indicated that in their persistent times, runoff and precipitation will continuously decline, whereas evaporation will continuously increase.

(2) Runoff and precipitation exhibited similar abrupt change features and stage characteristics, whereas the abrupt change times of evaporation lagged 1–2 year(s) behind those of runoff and precipitation as a whole.

(3) The periodic changing characteristics of runoff were similar to those of precipitation, but showed an inverse correspondence with that of evaporation.

(4) The contribution of precipitation to runoff change was stable and high at 50%–60%. The contribution of evaporation to runoff change markedly changed with a positive or negative effect of 10%–90%. Meanwhile, the contribution of human activities to runoff change maintained a relatively lower positive or negative effect of 20%–60%.

(5) Climate factors highly contributed to runoff change. By contrast, the contribution of human activities to runoff change was low. The contribution of climate factors to runoff change was highly variable because of differences among base periods. When the effects of evaporation were considered, the contribution of human activities to runoff change gradually increased but remained relatively stable over different periods when ignoring it.

Acknowledgement

This research work was supported jointly by National Key Research Program of China (No. 2016YFC0502300, 2016YFC0502102, 2013CB956700 & 2014BAB03B02), United Fund of Karst Science Research Center (No. U1612441), International cooperation research projects of the National Natural Science Fund Committee (No. 41571130074 & 41571130042), Science and Technology Plan of Guizhou Province of China (No. 2012-6015 & 2013-3190 & 201742920512120000), Science and Technology Cooperation projects (No. 2014-3).

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