Comprehensive analysis on the evolution characteristics and causes of river runoff and sediment load in a mountainous basin of China's subtropical plateau

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1 Introduction

Runoff generation and sediment transport are the two complex dynamic processes in surface water and soil systems, which are of essential importance for flood mitigation, river channel training and river management (Chen *et a*l., 2001). Climate variability and human activities in a river basin can result in alterations to the runoff and sediment processes. Climate variability such as the increase of precipitation, may cause the increase of surface runoff and the enhancement of soil erosion, and eventually leads to the increase of river sediment. On the other hand, human activities such as land-use changes, urbanization, soil conservation and dam construction, will lead to the change of river runoff and sediment in time and space. During the past decades, 24% of the world's large rivers have experienced significant changes in water flux and 40% in sediment flux, most notably declining trends in water and sediment fluxes in Asia's large rivers and an increasing trend in suspended sediment concentrations in the Amazon River (Li et al., 2020). With the rapid development of social economy, the impact of human activities on water and soil systems is increasingly prominent. Since human disturbances cause substantial changes to the runoff and sediment regimes, at present few rivers are in a natural state all over the world.

Rivers have a characteristic runoff regime that captures the typical pattern of fluctuations in the magnitude, timing and frequency of runoff across a given year (Murphy, 2020). Under stationary climate and limited human influences, these fluctuations can be expected within the ranges for a given runoff regime. However, runoff regime may be changed systematically over time due to strong interference of natural and anthropogenic factors. For example, mean runoff will increase when regional climate enters a humid period, the frequency of large fluctuations of runoff events may decrease due to reservoir construction or afforestation in the river basin (e.g. Ye et al., 2018). These changes in runoff regime are of great significance for the understanding of long-term water-quality and ecological alterations of river basins. In addition, the change of runoff regime may eventually lead to the change of river sediment load due to the modification in processes of sediment transport and riverbed erosion (Zhang et al., 2012; Wang et al., 2013; Yang et al., 2015). In order to adopt water resources management and land planning, researches on the evolution and driving mechanism of runoff and sediment under the changing environments have been focused considerably on hydrology over the past decades (Zhang et al., 2006; Gebremicael et al., 2013).

Quantitative assessment and separation of the impacts of climate variability and human activities on runoff and sediment changes has always been an important hot issue. Generally, there are two main approaches, process-based and statistical-based, were used to evaluate the contributions of climate variability and human activities to streamflow change. The former method mainly based on hydrological modelling by changing inputs of meteorological and land use scenarios (Petchprayoon et al., 2010; Tesfa et al., 2014; Madani et al., 2017; Li et al., 2019; Chen et al., 2019). Statistical method mainly includes the empirical regression analysis and climate elasticity analysis. Especially, the climate elasticity analysis, also known as hydrological sensitivity analysis, is a common method in quantifying the influence of changes in precipitation and potential evaporation on streamflow in recent years (Roderick and Farquhar, 2011; Ye et al., 2013; Wu et al., 2017). Similarly, attempts to evaluate the impacts of climate variability and human activities on river sediment change have been widely conducted (e.g. Tang et al., 2013; Zhao et al., 2017, 2018; Wei et al., 2017; Lacher et al., 2019; Murphy, 2020; Huang et al., 2020; Martínez-Salvador & Conesa-García, 2019). Zhao et al. (2018) systematically reviewed six quantitative methods in analyzing the response of sediment change to climate variability and human activities, including the simple linear regression, double mass curve, sediment identity factor analysis, dam-sedimentation based method, the Sediment Delivery Distributed (SEDD) model, and the Soil Water Assessment Tool (SWAT) model. They concluded that five methods produced similar estimates except for the linear regression based on a case study in the Huangfuchuan watershed on the northern Loess Plateau. It is worth noting that each method has its merits and disadvantages. Even though the most popular process-based models (such as SWAT) have great applicability in evaluating the impacts of climate variability and human activities on runoff and sediment processes, the requirement of large amount of observed input data and low computational efficiency might limit their wide application in those large river basins. Because that concentration (or load) of annual mean sediment is related to annual streamflow conditions, in the attribution analysis of sediment change, methodology of most researches is based on the statistical relationship between sediment, runoff or precipitation (e.g. Wang et al., 2007; Li et al., 2016; Zhao et al., 2018; Wu et al., 2019). For example, Murphy (2020) explored contributions to sediment trends from changes in land management versus changes in the streamflow regime through the analysis of concentration–streamflow relationship over time. Actually, in this way, the impact factors of climate variability other than precipitation are not well considered, or runoff itself is usually regarded as an impact factor, therefore the relative role of climate variability and human activities cannot be clarified theoretically. Up to now, scientists have been seeking for better approaches in quantifying the contributions of climate variability and human activities on streamflow and sediment variations.

The Guizhou Province is a mountainous area in southwestern China. It is also one of the main karst zones in the world (Parise et al., 2009). In this region, mountains and plateaus are widely distributed and rivers are well developed. As a spatially open double-layer hydrological system (Song et al., 2017), water and soil resources are easy to be eroded from the surface and underground in karst area (Feng et al., 2016; Wang et al., 2019b). For a long time, due to the influence of geological background and man-made destruction, rocky desertification landscapes are widely distributed in the Guizhou province (Cao et al., 2016; Yan et al., 2018). During the past decades, serious soil erosion in the Guizhou province has led to barren soil, reduction of cultivated land area and frequent droughts and floods, restricting the sustainable development of regional economy (Wang et al., 2019a). Since the 1970s, extensive construction of hydropower stations has been conducted in the river basins of the Guizhou Province (Wang et al., 2015). In recent years, in order to control soil erosion and restore local ecology in the western China, a series of China’s national strategies have been implemented, such as the projects of ecological environment construction and soil and water conservation in the middle and upper reaches of the Yangtze River. These large scale human activities have considerably modulated river discharge in time and space and reduced sediment load from hillslopes to river channels (Xiong et al., 2008; Wang et al., 2015; Wu et al., 2018; Guan et al., 2019). Attributing runoff and sediment trends to the effects of climate variability and human activities at the catchment scale can provide a profound understanding of the relative contribution of largely controllable human influences on river runoff and sediment, resulting from changes in land management and surface disturbance, compared to that of less controllable changes in the climate regime. The result of attribution analysis is critical for the sustainable development of water resource and terrestrial ecosystems.

In this paper, we selected the Wujiang River basin (WRB), a large mountainous river basin in Guizhou Province, southwestern China, as the study site for analyzing the responses of annual runoff and sediment load to climate variability and human activities by using an integrated approach. The objectives of this study are: (1) to present an integrated approach for analyzing the evolution characteristics, including the trend, periodicity and correlation of the runoff and sediment load over time; (2) to quantify the impacts of climate variability and anthropogenic activities on the change of runoff and sediment load, and (3) to link specific climate variability, implementation of soil and water conservation, and extensive construction of hydropower stations to the changes of river runoff and sediment load. This study provides a basic framework for analyzing the evolution characteristics and causes of runoff and sediment load. What is particularly important is that we fully consider the result of the attribution analysis of runoff change in quantifying sediment load changes. Our results not only provide theoretical basis in guiding soil and water conservation and local ecology restoration in the WRB, but also provide a good reference for the comprehensive investigation of runoff and sediment changes in similar regions all over the world.

2 Materials and methods

2.1 Study area

The Wujiang River, located in southwestern China, is one of the major tributaries in the upstream basin of Yangtze River with an average annual flow of 1627 m^3/s (Fig.1). The river runs about 1037 km through the west, middle and northeast of Guizhou province and discharges into the Three Gorges reservoir at Fuling District of Chongqing city. The Wujiang River basin (WRB) covers an area of 87, 900 km^2, where 75.6% of the area is covered by carbonate rocks (Xiong et al., 2008). Major landforms of the WRB are mountain plateau, middle low mountains and hills. Average altitude of the basin is about 1160 m above mean sea level (a.m.s.l.) and it ranges from 160 to 2800 m a.m.s.l. There are 15 large tributaries in the basin, with the largest being Liuchong River, Maotiao River, Qingshui River and Hongdu River. The upper, middle and lower reaches of the WRB are bounded at Yachihe and Sinan hydro-stations (Fig. 1). Historically, the WRB is a moderate soil erosion area in the upper reaches of the Yangtze River, with an average annual soil erosion of 1187 t/km^2 (Guan et al., 2019). Due to spatial difference of soil erosion, river sediment load mainly comes from the upper reaches of the WRB disproportionally. According to observations, mean annual discharge at Yachihe is 350 m^3/s, which is about 39% of the Sinan station and 22% of the Wulong station. However, mean annual sediment yield in the upstream basin above Yachihe station is 1687×10^4 t, which is about 77% of the basin above Sinan station and 43% of the basin above Wulong station.

Fig. 1. Insert here

Climatically, the WRB belongs to a subtropical climate zone except some west headwater areas with altitude above 2000 m a.m.s.l. Average annual precipitation of the basin is 900–1400 mm and average annual temperature is 13.02–17.53°C. Annual precipitation in the catchment shows a distinct wet and a dry season. More than 65% annual precipitation is concentrated in the wet season from April to August (Fig. 1).

Due to large changes of surface elevation and strong cutting of the rivers, the WRB is rich in hydropower resources. It is an important base for the "West-East Electricity Transmission Project" in China. Potential hydropower of the whole basin is 10.43 million KW, of which, the main stream of the Wujiang River is 5.80 million KW. Since the 1970s, there are 11 cascade hydropower stations have been built on the main stream of the

Wujiang River (Fig. 1). Among which, the reservoir dam of Wujiangdu hydropower station is 162 meters high, which is the largest high dam that has been built in the karst area of China.

2.2 Available data

In this paper, we use data from Wulong hydro-station to investigate the characteristics of hydrological and sediment changes in the whole WRB. The Wulong hydro-station, located on the lower mainstream of the Wujiang River, is the outlet control hydro-station of the whole basin with a gauging area of 83, 053 km^2. Annual series of runoff and suspended sediment load of the Wulong station during 1970–2016 were collected from Changjiang Sediment Bulletin 2016. The Changjiang Sediment Bulletin is published every year and can be accessed freely on the website (http://www.cjh.com.cn/en). The monitoring of river runoff was based on the standard current meter measurement (GB 50179-2015, 2015), while the monitoring of suspended sediment load was based on the cross-section sampling and the corresponding runoff data (GB/T 50159-2015, 2015). There are documents of standard procedures used to collect runoff and sediment load data. All these were completed by the local hydrological station. According to the observed water and sediment processes, the daily, monthly and annual runoff and sediment load of the river can be calculated.

Meteorological data from 12 weather stations across the WRB (see Fig. 1) were obtained from National Climate Centre of China Meteorological Administration (CMA). The data include daily precipitation, temperature (maximum, minimum and mean), relative humidity, sunshine duration, and wind speed among others during the period 1970–2016, and with no missing data on the variables. All the climate variables provided by CMA had gone through a standard quality control process before delivery (QX/T 66-2007, 2007). Based on the meteorological datasets, daily potential evaporation of the weather stations was estimated by the Penman-Monteith equation (Allen et al., 1998) which is recommended by the Food and Agriculture Organization (FAO) of the United Nations. Daily precipitation and potential evaporation were aggregated to obtain annual data of each weather station. In consideration of the large degree of variation in topography and the uneven distribution of weather stations across the catchment, an area based weighting method was used to calculate the average precipitation, potential evaporation for the whole catchment. The weight coefficient, expressed by the percentage of the area represented by each meteorological station, was calculated using the Thiessen Polygon method.

In addition, eight consecutive survey data of national forest resources of China completed in 1973–1976, 1977–1981, 1984–1988, 1989–1993, 1994–1998, 1999–2003, 2004–2008, 2009–2013, respectively, were obtained from China Forestry Database. The data collection of forest resources was mainly based on the method of fixed sample plot survey. In recent years, the interpretation of satellite remote sensing image was applied as a supplementary method. According the eight consecutive survey data of national forest resources, the forest coverage data of each time in the Guizhou Province were then extracted. In addition, the basic information, such as operation year and reservoir volume of the major hydropower stations on the mainstream of Wujiang River, was also collected.

All the data used in the paper can be freely accessed in the supplementary files.

2.3 Methodologies

Fig. 2 shows the framework of this study to investigate the evolution characteristics and causes of the runoff and sediment load in the WRB. Firstly, the evolution characteristics of the annual runoff and sediment load including the trend, periodicity, change point and their correlations were systematically analyzed by using the related methods based on the observed data during the period 1970–2016. Secondly, according to the evolution characteristics, annual runoff and sediment load time series were divided into a baseline period and several changing periods. On this basis, the contributions of climate variability and human activities on runoff change were first distinguished by using a widely applied Budyko-based hydrological sensitivity method, and then the result was further applied in the attribution analysis of river sediment load change.

Fig. 2. Insert here

2.3.1 Identification and characterization of runoff and sediment regimes

In this study, an ordinary linear regression method in the form of $\hat{y} = \alpha t + b$ and the least squares method were applied to analyze the time trend of the annual runoff and sediment load. In this equation, α and b are the regression coefficients with α estimates the slope (change rate) and b represents the interception, t is an independent time variable, $\hat{y}$ is the dependent series of annual runoff or sediment load. The slope (α) of the regression indicates the direction and magnitude of the temporal change: positive slopes ($\alpha > 0$) and negative slopes ($\alpha < 0$). The significance of the linear trend was further estimated by the Mann-Kendall test (Mann, 1945; Kendall, 1975).

The continuous wavelet transform (CWT) was applied to study the periodicity of annual runoff and sediment load series of the WRB. The CWT is a signal processing method that has been widely used for analyzing localized variations of power within a geophysical time series (e.g., Torrence and Compo, 1998; Zhang et al., 2009; Ye et al., 2016). Through CWT analysis, hydro-meteorological series can be decomposed into time–frequency space to determine both the dominant modes of variability and how those modes vary in time (Torrence and Compo, 1998). Due to good balance between time and frequency localization, Morlet wavelet was chosen as a basic wavelet when applied the CWT method (Ye et al., 2016).

The cumulative anomaly method, a non-linear statistical method to judge the change trend of discrete data points, was applied to detect potential change point of hydro-meteorological series. The kernel of cumulative anomaly is to judge the discrete amplitude of the discrete data to its mean value. If the cumulative anomaly increases, it indicates that the discrete data is larger than its mean value, otherwise the decrease of cumulative anomaly indicates that the discrete data is smaller than its mean value (Ran et al., 2010). If the curve of cumulative anomaly is composed by the two parts of increase and decrease, then the break point of the change trend can be determined. In order to verify the result from visual evaluation of this method, the T-test was further used to analyze the mean difference before and after the change point (Joan, 1987).

In addition, the double mass analysis was applied to detect the changes of relationship between precipitation, runoff and sediment load. The method was initially used to examine the consistency of hydrological or meteorological data. In recent years, it has been widely applied in the assessment of the response of river discharge/sediment load to climate variability and human activities (e.g., Ma et al., 2012; Gao et al., 2017). The double mass analysis is composed of cumulative values of two parameters plotted against one another over a certain time span. Slope breaks in the curve may indicate the change in relationship between the studied variables, which can be driven by various factors, such as urbanization, revegetation or deforestation, soil and water conservation measures and climate variability. Most importantly, the slope breaks are able to help determine the change point year of a geophysical time series (Searcy and Hardison, 1960). Furthermore, the ANCOVA method (Wright, 2011) was used to test the significance of the slope difference between the two lines before and after the change points.

2.3.2 Attribution analysis on the change of annual runoff

For a natural basin, the water balance can be described as:

$$P = ET + R + \Delta S/\Delta t \quad (1)$$

where P is precipitation, ET is actual evapotranspiration, R is runoff, and the unit of all the above variables is *mm/year* and ΔS is the change in basin water storage with unit of *mm*. Over a long period of time (i.e., 10 years or more), ΔS can be reasonably assumed as zero.

Following the mathematical expression of Budyko-Fu (Fu, 1981), a famous Budyko-type hypothesis in describing water and energy balances, the long-term mean annual actual evapotranspiration (ET) can be estimated as follows:

$$ET/P = 1 + \emptyset - (1 + \emptyset^m)^{1/m} \quad (2)$$

where $\emptyset$ is termed "dryness index", which equals to ET_p/P (ET_p is potential evaporation); m is empirical parameter that determines the shape of the Budyko-Fu curve and reflects the impact of other factors such as land surface characteristics and climate seasonality on water and energy balances (Li et al., 2013). The details of the equation can be found in Fu (1981). The parameter m in Equation (2) can be calibrated by comparing the long-term annual ET calculated from the observed P and R in the Equation (1).

Based on the principle of hydrologic sensitivity proposed by Milly and Dunne et al. (2002), the change in runoff caused by climate variability (precipitation and potential evaporation) can be approximated as follows:

$$\Delta \mathrm{R}_{clim} = \frac{\partial R}{\partial P}\Delta P + \frac{\partial R}{\partial ET_p}\Delta ET_p \tag{3}$$

where ΔP and $\Delta \mathrm{ET}_p$ are the average changes in precipitation and potential evaporation in two different periods, respectively; $\frac{\partial R}{\partial P}$ and $\frac{\partial R}{\partial ET_p}$ represent the sensitivity coefficients of runoff to precipitation and potential evaporation, and can be further expressed based on the formula of Budyko-Fu:

$$\frac{\partial R}{\partial P} = (1+\emptyset^m)^{1/m} - \emptyset(1+\emptyset^m)^{(\frac{1}{m}-1)} \tag{4}$$

$$\frac{\partial R}{\partial ET_p} = \emptyset^{(m-1)}(1+\emptyset^m)^{(\frac{1}{m}-1)} - 1 \tag{5}$$

With the calculated $\Delta \mathrm{R}_{clim}$, the impact of human-induced change in runoff ($\Delta \mathrm{R}_{hum}$) can therefore be obtained as:

$$\Delta \mathrm{R}_{hum} = \Delta \mathrm{R} - \Delta \mathrm{R}_{clim} \tag{6}$$

The relative contributions of climate variability and human activities on runoff change can be further expressed as:

$$\eta_{clim-R} = \frac{\Delta \mathrm{R}_{clim}}{|\Delta \mathrm{R}|} \times 100\% \tag{7}$$

$$\eta_{hum-R} = \frac{\Delta \mathrm{R}_{hum}}{|\Delta \mathrm{R}|} \times 100\% \tag{8}$$

where η_{clim-R} and η_{hum-R} are the percentages of the impact of climate variability and human activities on streamflow, respectively.

2.3.3 Attribution analysis on the change of river sediment load

The transport of river sediment is accompanied by runoff. Usually, annual sediment load of a river increases with annual river discharge because more water discharge will have more power to transport more sediment. Numerous researches have shown that there exists a good correlation between the two variables (e.g., Zheng et al., 2012; Guo et al., 2017). However, disturbance of human activities, especially tremendous influences from water reservoirs will cause change of this correlation (Guan et al., 2019).

For a period when human activities are relatively weak (the baseline period), the correlation between annual runoff and sediment load of a river can be simplified as:

$$\mathrm{S}_b = f(\mathrm{R}_b) \tag{9}$$

where S_b and R_b are annual sediment load and runoff series, respectively. Normally, the relationship can be described as a power function (e.g. Ran et al., 2009; Wu et al., 2019).

If the external environmental conditions continue, annual river sediment load in other periods can be re-constructed as:

$$\mathrm{S}_{sim-c} = f(\mathrm{R}_c) \tag{10}$$

where S_{sim-c} is the re-constructed sediment load and R_c is the observed runoff.

With reference to the baseline period, actual change of river sediment load in other periods (ΔS) is given as:

$$\Delta S = \mathrm{Ave\_S}_p - \mathrm{Ave\_S}_b \tag{11}$$

where $\mathrm{Ave\_S}_p$ and $\mathrm{Ave\_S}_b$ are average annual sediment load series in the other periods and the baseline period, respectively.

Average change of sediment load caused by runoff change (ΔS_R) can be calculated as:

$$\Delta S_R = \mathrm{Ave\_S}_{sim-c} - \mathrm{Ave\_S}_b \tag{12}$$

where $\mathrm{Ave\_S}_{sim-c}$ is the predicted average annual sediment load in the other periods.

It is known that runoff change itself is affected by climate variability and human activities, therefore, the impact of climate variability on river sediment load (ΔS_{clim}) can be further considered as:

$$\Delta S_{clim} = \Delta S_R \times \eta_{clim-R} \tag{13}$$

The impact of human-induced change in sediment load (ΔS_{hum}) can be obtained as:

$$\Delta S_{hum} = \Delta S - \Delta S_{clim} \tag{14}$$

The relative contributions of climate variability and human activities on sediment load change can be expressed as:

$$\eta_{clim-S} = \frac{\Delta S_{clim}}{|\Delta S|} \times 100\% \tag{15}$$

$$\eta_{hum-S} = \frac{\Delta R_{hum}}{|\Delta S|} \times 100\% \tag{16}$$

where η_{clim-S} and η_{hum-S} are the percentages of the impact of climate variability and human activities on sediment load, respectively.

3 Results

3.1 Change patterns of annual runoff and sediment load

3.1.1 Annual trends and variability

Fig.3 shows the variation of annual runoff depth and sediment load of Wulong station during 1970–2016. It is obvious from the figure that both variables are characterized by inter-decadal fluctuation. Annual runoff was relatively large from the mid-1970s to the mid-1980s, and from the mid-1990s to the mid-2000s, while relatively small from the mid-1980s to the mid-1990s, and from the mid-2000s to the mid-2010s. The maximum and minimum of annual runoff depth were 829.59 mm and 346.41 mm respectively, which occurred in 1977 and 2006. The variation of sediment load at Wulong station is more prominent. Annual sediment load and its fluctuation were relatively large from 1970 to mid-1980s, and then reduced remarkably until the earlier 2000s. Since the mid-2000s, annual sediment load of Wulong station has been further reduced to a very small level, and so does the variation amplitude. The maximum annual sediment load in 1977 was 2 orders of magnitude larger than the minimum in 2013.

In terms of long-term trend, annual runoff depth of Wulong station showed a slight decreasing, but non-significant trend ($p > 0.1$) at a linear rate of –17.2 mm every 10 years. Annual sediment load, however, showed a significantly decreasing trend ($p < 0.01$) at a linear rate of 901×10^4 t every 10 years.

Fig. 3. Insert here

3.1.2 Periodic characteristics

The analysis of wavelet power spectra demonstrates the pronounced inter-annual and decadal variability of the runoff and sediment load of Wulong station. Continuous wavelet power spectrum in Fig. 4a indicates that energy centers of frequency space are mainly concentrated in 15 to 25 year bands, 5 to 10 year bands and < 5 year bands. This observation demonstrates that there exist three possible periodicities for the annual variability of runoff during 1970–2016. According to the result of wavelet variance, it is clear that the average primary periodicity of runoff of Wulong station is about 22 years, and the two secondary periodicities are 7 and 4 years, respectively (Fig. 4b). Further analysis from the distribution patterns of wavelet power spectrum in Fig. 4a indicates that the runoff of WRB has experienced a periodic evolution process of high, low, high, low, and high during 1970–2016 at the scale of 22 years primary periodicity. By the end of 2016, the WRB was still in the period of high runoff. However, the result from Fig. 4a also demonstrates that the length of primary periodicity of 15–25 years shows a decreasing trend during the study period. The medium length periodicity of 5–10 years disappeared during 1986-2008.

Fig. 4. Insert here

The result of continuous wavelet transform of sediment load is somewhat different from that of runoff. As shown in Fig. 5a, the energy centers of frequency space are mainly concentrated in 20 to 30 year bands and 5 to 10 year bands. Compared to the result of runoff, only two periodic components can be identified for annual sediment load. Although both have medium length periodicity of 5–10 years, the length of primary periodicity of sediment load is little longer. In addition, the energy centers of both timescales weakened gradually during the study period. Especially, energy centers in the timescale of < 5 year has almost disappeared since 2010. Result from wavelet variance indicates that annual sediment load of Wulong station exists a primary periodicity of 25 years, and a secondary periodicity of 7 years (Fig. 5b).

Fig. 5. Insert here

3.1.3 Step change characteristics

In order to eliminate the unit limitation of data and facilitate the comparison of variables of different units or magnitudes, we first use the Min-max normalization method (Ji et al., 2016) to standardize the original data series. Fig.6 shows the cumulative anomaly curves of the standardized sequence of precipitation in the WRB, and runoff depth and sediment load at Wulong station during 1970–2016. It can be seen that the variation of cumulative anomalies of annual precipitation and runoff is highly consistent. There are three change points in 1984, 1994 and 2004 can be clearly detected from visual inspection. The trend of annual precipitation and runoff sequences before and after the change points is obviously opposite in sign. T-test further demonstrates that there are significant differences ($p < 0.05$) in the mean values of runoff and sediment before and after the three change points. Take the three step change years as the boundary, annual precipitation and runoff series in the WRB can be divided into four stages of high, low, high and low during 1970–2016. This result is very similar to that of the periodicity analysis of runoff in Fig. 4. In which, runoff of the WRB has experienced two cycles of high and low during the study period. According to the discrete amplitude (Fig. 6), the analysis of cumulative anomaly further indicates the relative fluctuation of annual runoff was smaller than that of precipitation before 1984, while it changed to be bigger afterwards. However, the differences of relative fluctuation between annual precipitation and runoff during the two periods before and after 1984 were not significant by the T-test.

Step change of annual sediment load of the WRB was also occurred in 1984 and 1994. Different from annual precipitation and runoff, no change point can be observed at 2004. Instead, a change point in 2000 was found. Similarly, the three change points were further validated by the T-test ($p < 0.05$). The relative fluctuation of annual sediment load of the WRB was much bigger than that of precipitation and runoff.

Fig. 6. Insert here

3.1.4 Changes of relationship between precipitation, runoff and sediment load

The calculated double mass curves of cumulative precipitation versus cumulative runoff, and cumulative runoff versus cumulative sediment load are presented in Fig. 7. It is clear from the figure that the slope of the curves changed in some places. Good linear relationship between the two cumulative variables can be observed in the two sides of slope breaks. From visual inspection, the results in Fig.7a show that there exists a slight slop change in the cumulative curve of precipitation versus runoff, where the slope of the curve decreased after 2005. However, the ANCOVA test demonstrates that the slope difference between the two fitted lines before and after 2005 was significant ($p < 0.05$). The change of the correlation between runoff and sediment load is quite prominent. Three major slope change places can be observed in the cumulative curve of runoff versus sediment load (Fig.7b). The potential change-points were occurred around 1983, 1995 and 2005. In the initial period of 1970–1982, the slope of the curve was quite steep. While, it decreased gradually in the following periods of 1983–1994, 1995–2004 and 2005–2016. Especially, the slope of the curve during 2005–2016 was very small, and close to a horizontal line. The ANCOVA test demonstrates that the slope difference between the fitted lines before and after the change points were significant ($p < 0.05$).

Fig. 7. Insert here

The changed precipitation-runoff and runoff-sediment load relationships indicate significant regime changes of runoff and sediment processes in the WRB during the study period. Generally, this change is more prominent for sediment load. According to the double mass curves, the slope of fitted linear lines in each segment represents the runoff coefficient or sediment concentration during the corresponding time period. Result from Fig. 6a indicates that runoff coefficient during 1970–2004 was about 0.536, while it decreased to 0.491 after 2005. Sediment concentration was about 741 mg/L, 379 mg/L, 339 mg/L and 78 mg/L during the periods 1970–1982, 1983–1994, 1995–2004 and 2005–2016, respectively. Mean concentration during the 1970–1982 period decreased by 362 mg/L on the basis of the 1983–1994 period, and the number is 261 mg/L between the 1995–2004 period and the 2005–2016 period. The sediment decrease was more prominent for the 1983–1994 period, than for the 2005–2016 period.

3.2 Runoff and sediment load changes in different periods

In consideration of the results of both cumulative anomaly analysis and double mass analysis, as well as the potential periodic characteristics, annual series of precipitation, runoff and sediment load of the WRB during the study period can be divided into four different periods: 1970–1984, 1985–1994, 1995–2004 and 2005–2016. Among them, the basin was in a relatively wet period during 1970–1984 and 1995–2004, while the other two periods were relatively dry. During the period 1970–1984, the relative fluctuation of runoff was marginally less than that of precipitation (Fig. 6), which well reflects the natural processes of rainfall-runoff in this karst basin. Variations of runoff and sediment load in the other periods were obviously disturbed by more human activities.

Based on the above division of the four periods, the average value of runoff and sediment in different periods was calculated. Result from Table 1 shows that annual runoff and runoff coefficient were relatively larger in the period of 1970–1984 and the period of 1995–2004. During the period 2005–2016, both the runoff depth and runoff coefficient were the minimum in the last four time periods. Average annual sediment load at Wulong station was 3734×10^4 t during period of 1970–1984, while the value reduced dramatically to 1604×10^4 t in the following period of 1985–1994. However, average annual sediment load shows a slight increase in 1995–2004 with reference to the former period. In the period 2005–2016, average annual sediment load reduced to a very small value of 363.33×10^4 t. Sediment concentration decreased gradually from 716 mg/L to 84 mg/L in the last four time periods. Even in the period of 1995–2004 when sediment load increases relative to the former period of 1985–1994, the sediment concentration still decreased.

Table 1 Insert here

3.3 Contribution of climate variability and human activities between periods

3.3.1 Runoff

In the application of hydrologic sensitivity analysis method to runoff change attribution analysis, m is a main model parameter. We calibrated m by comparing long-term annual ET calculated by using Equation (2) and the water balance equation (1) for the relative natural period 1970–1984. After manual trial and error, the optimized value of m is 1.71 for the WRB. When m=1.71, the values of sensitivity coefficients $\partial R/\partial P$ and $\partial R/\partial ET_P$ were 0.72 and -0.29, respectively. This result reveals that the change in runoff was more sensitive due to precipitation (P) than to potential evaporation (ET_P) in this region.

According to hydrological sensitivity analysis, all the calculated parameters were then used to estimate the impact of climate variability on the change of runoff reference to the baseline period 1970–1984. Table 2 lists the quantified result of the impacts of climate variability and human activities separated by the method. As presented in Table 2, the effects of climate variability and human activities varied in different periods. With reference to the baseline period, the contribution rate of climate variability to the runoff change was relatively large during the period 1985-1994. Both the contribution rates of climate variability and human activities to runoff change were roughly the same between the period 1995–2004 and the period 2005–2016, but their impact directions are different in the two periods. Generally, quantified result indicates that with reference to the baseline period 1970–1984, regional climate variability was always the main cause for runoff change, not only in the relatively dry periods of 1985–1994 and 2005–2016, but also in the relatively wet period of 1995–2004. In addition, climate variability and human activities show the same effect direction on runoff change, both are positive or negative in the changing periods.

Table 2 Insert here

3.3.1 Sediment load

According to the annual variation of runoff and sediment load measured at Wulong station, the functional correlation between the two variables was first established for the baseline period 1970–1984. By comparing several kind of fitting functions (such as exponential function; linear function; logarithmic function; polynomial function and power function), the power function was finally confirmed to be the best fitting function in describing the relationship between annual runoff and sediment load. As shown in Fig. 8, the fitted power function for the baseline period was $S = 1.7283R^{1.2231}$ (where S and R are annual sediment load and runoff with units of 10^4t and 10^8m^3). In the other periods, the fitted power function was obviously changed. Overall, the fitted curve of power function in the following three periods declined obviously, indicating that the sediment load measured at Wulong station decreased significantly under the same runoff condition.

Fig. 8. Insert here

Table 3 lists the quantified impacts of climate variability and human activities on sediment change in the WRB. With reference to the baseline period 1970–1984, it is obvious from the table that human activities, rather than climate variability, dominate the decrease of sediment load in the WRB. With reference to the baseline period, the average reduction of annual sediment load was 2130×10^4 t in the period 1985–1994, the contribution rate of climate variability was 32.8%, while that of human activities was 67.2%. In the following period 1995–2004, the average reduction of annual sediment load was 1740×10^4 t. However, relative increment of sediment load due to runoff increase was 130.26×10^4 t, and so human activities resulted in a total reduction of 1870.26×10^4 t sediment load. Therefore, the effect of climate variability to sediment load reduction is negative, and the contribution rate was -7.5%, while the contribution of human activities reached to 107.5%. In the period 2005–2016, the average reduction of annual sediment load reached to extraordinary level 3370×10^4 t. The contribution rate of climate variability to the sediment load reduction was 17.7%, and human activities was 82.3%.

Table 3 Insert here

4 Discussion

Variations of annual runoff in the WRB are mainly influenced by natural factors, especially precipitation changes. However, the source of river sediment mainly comes from slop soil erosion of overland flow, the conditions of underlying surface such as vegetation cover, topography, water conservancy project, etc. have important impacts on sediment load. Normally, soil erosion on the slope more than 15° decreases obviously with the increase of vegetation coverage (Wu et al., 2018). Generally, due to the special double-layer hydrological system in the karst area, the underlying surface has limited effect on regulating, storing and distributing precipitation, and soil and water resources are easy to be lost in these processes (Song et al., 2017). Our observation revealed that the differences of relative fluctuation between annual precipitation and runoff during the study period were not significant (Fig. 6). This result further confirms that the underlying surface of the WRB has a weak role in regulating and distributing precipitation. In the WRB, linear correlations between annual precipitation and runoff were always significant during the study periods, however, the linear correlations between annual precipitation and sediment load were not significant during the periods of 1985–1994 and 2005–2016 (Fig. 9). The correlation coefficient between precipitation and sediment load was considerably lower than that between precipitation and runoff, indicating annual sediment loads incorporate additional variability from sources other than precipitation, a large portion of which is attributable to human activities.

Fig. 9. Insert here

Like many regions in China, the Guizhou Province has undergone intensive human activities. Among which, the changes of land use/land cover and dam construction are the two essential human activities that may have exerted considerable impacts on runoff and sediment processes. The result of the eight continuous surveys of national forest resources indicates that forest coverage of the Guizhou Province has changed greatly during the past decades (Fig. 10). Because the Guizhou province is a typical karst mountainous region in China, rock desertification is quite common and the overall forest coverage is low. Since the 1960s, large-scale industrial and agricultural development has gradually started. Slope planting in mountainous area and river valleys resulted in destruction of vegetation cover. Forest coverage of the Guizhou Province dropped to the lowest level in the earlier 1980s (Fig. 10). For this reason, sediment load of the Wujiang River was obviously higher during the baseline period of 1970–1984. Since the mid-1980s, the implementation of soil and water conservation has been carried out in the Guizhou Province, such as the projects of slope farmland management, afforestation, returning farmland to forest and small water conservancy construction (Zhang, 2016; Gu et al., 2018). In particular, the wide implementation of slope farmland transformation and returning farmland to forest played an important role in restraining soil erosion. During the past four decades, 84.51% area of the WRB showed an increasing trend of vegetation coverage, especially in the middle-lower basin, however, the area with decreasing trend of forest coverage mainly distributed in the upper basin and along the riverside (Zheng et al., 2018). Relevant studies revealed that human activities play a dominant role in the change of vegetation coverage in WRB (Shi et al., 2017; Zheng et al., 2018). It should be noted that the initial work of water and soil conservation and returning farmland to forest progressed slowly, and the effect on reducing river sediment was not significant in the 1980s. For example, study by Wu et al. (2018) pointed out that sediment load at Hongjiadu station was basically the same in 1970s and 1980s under the same condition of river runoff. Only in the later 1990s, after a long time period of soil and water conservation, can the condition of soil erosion in the basin be greatly improved. Normally, it is a gradual process for human activities to affect river discharge and sediment by changing the underlying surface of the river basin. After all, large-scale basin development, soil and water conservation, and afforestation/deforestation need many years to complete, and their impacts on runoff and sediment processes are gradually increasing or decreasing.

Fig. 10. Insert here

It is known that most of the hydropower stations have limited influence on the long-term change of river annual runoff, however, the construction of hydropower stations on rivers can have an immediate impact on sediment load (Gao et al., 2011; Ibanez, 2015). Up to now, there are 11 cascade hydropower stations have been completed and put into operation on the mainstream of the Wujiang River (see in Fig. 1). Fig. 11 shows the variation of cumulative reservoir volume according to the operation of the hydropower stations. Because serious soil erosion and degradation of ecological environment in the WRB are mainly concentrated in the upstream areas (Lu et al., 2018; Guan et al., 2019), the operation of Wujiangdu hydropower station in 1982, Dongfeng hydropower station in 1994, and Hongjiangdu hydropower station in 2004 was overall consistent with the sharp reduction of sediment load and the changed relationship between runoff and sediment load at Wulong station during the changing periods, indicating that the operation of hydropower stations has a decisive impact on the interception of river sediment load.

Fig. 11. Insert here

The results of our investigation confirmed the earlier conclusion that human activities (such as soil and water conservation, afforestation, hydropower station construction, etc.) exert more influences on the change of annual sediment load than on runoff (Gao et al., 2011; Ibanez, 2015). This result is quite common all over the world. Li et al. (2020) revealed that the change of precipitation is found significantly correlated to the change of water flux in 71% of the world's large rivers, while dam operation and irrigation rather control the change of sediment flux in intensively managed catchments. It should be noted that human activities have a positive effect of increasing runoff in the WRB during the period 1995–2004 with reference to the baseline period, which is different from the result of the other periods. The main reason lies in the serious destruction of the surface vegetation due to the prevailing of hydropower station construction in the basin during this period (Zheng et al., 2018; Guan et al., 2019). The slightly increased sediment load during 1995–2004 with reference to the former period of 1983–1994, also indicates the enhanced soil erosion in this period.

Based on the above analysis, it is easy to understand the change patterns of annual runoff and sediment load in the WRB. During 1970–2016, annual precipitation of the WRB showed a slight decreasing trend. This well explains the decreasing trend of river runoff. The increasing forest coverage, especially the construction of cascade hydropower stations in the basin is obviously responsible for the significant reduction of sediment load. In the Yangtze River basin, the periodicity of precipitation and runoff at different time scales has been widely observed. For example, runoff in the Poyang Lake basin exhibits three different timescales of periodicity: 25 year, 8 years and 3–4 years (Liu et al., 2009). Annual precipitation in the upper Yangtze River basin mainly varies under the periodicity of 4, 7 and 15 years (Sun et al., 2012). The periodic characteristics of this inter-annual variation are possibly correlated to the impacts of Asian monsoon and El Nino (Xiao et al., 2014; Zhang, 2015; Wang et al., 2016). However, our investigation further demonstrates that the length of the runoff periodicity of 15–25 years during the study period showed a decreasing trend. This feature has not appeared in other researches, and the reasons behind deserve further study. The periodicity of sediment load at Wulong station gradually weakened or even disappeared, indicating strong influence of accumulation of sediment interception in the reservoirs of hydropower stations.

In addition, the estimated step changes of precipitation and runoff according to cumulative anomaly analysis were highly consistent with the 22 years primary periodicity of runoff variation. This indicates that precipitation and runoff of the basin will change significantly during different dry and wet periods. However, the occurrence of change point for the correlations between precipitation, runoff and sediment load was somewhat different from the results of cumulative anomaly analysis, especially for the correlation between precipitation and runoff. The main reason is that the changes of precipitation and runoff are highly synchronous. Therefore, when the two variables become smaller/larger in the same proportion, the double mass curve is likely to keep the same slope so as to blur the possible change point. The observed change point years from the double mass curve of runoff versus sediment load are quite consistent with that of cumulative anomaly analysis. However, the exact determination of change point year from the double mass curve is inevitably to be arbitrary due to artificial inspection.

In this study, we provide a basic framework for analyzing the evolution characteristics and causes of river runoff and sediment load which can be referred in other relevant researches. Especially, we extend methods on previous studies by incorporating the result of attribution analysis of the runoff change in the attribution analysis of river sediment load change, which provides a new perspective for related research. In most of the previous studies river runoff was regarded as one influence factor besides human activities on sediment change attribution (e.g, Wang et al., 2007; Li et al., 2016; Guan et al., 2019; Murphy, 2020). As we know, runoff change itself is affected by climate change and human activities, and this impact will be more prominent under the context of intensified climate variability and anthropogenic stresses (Li et al., 2020). With comparison to previous studies, it is undoubtedly that the proposed method and quantified results in this paper have a better theoretical significance in attributing causes to temporal changes in sediment. However, there are also some weaknesses and uncertainties exist in our study. Firstly, we used meteorological data from 12 weather stations in the WRB which might not be enough to cover such a large basin with remarkable topographic changes. Secondly, the performance of the hydrologic sensitivity analysis and the fitted function for annual runoff and sediment load depends on the data of the baseline period, with no/limited effect of human activities. In reality, during the baseline period of 1970-1984, there were still human disturbances in WRB. Although the calibrated parameter (m) well reflects the average vegetation condition of the catchment, and the fitted power function for annual runoff and sediment load passed significant inspection during the baseline period, this could still affect the estimation results to some extent. In addition, from a practical point of view, it would be much more important to quantify the role of sediment accumulation in reservoirs and the role of reducing erosion intensity in the river basin. However, due to the different operation time of hydropower stations and the lack of long-term monitoring data of sediment load at the outlet of each hydropower station, further separation is currently impossible in this paper and leave for future studies.

5 Conclusion

In this study, we performed an integrated approach for analyzing the evolution characteristics and causes of runoff and sediment load in a typical mountainous river basin, the Wujiang River basin in southwestern China during 1970–2016. The main conclusions are summarized as follows:

(1) The change patterns of runoff and sediment load were well revealed by the integrated approach of trend, periodicity and step change. During the study period, annual runoff at Wulong station shows a slight decreasing trend, while a significant decreasing trend exists for sediment load. Annual runoff exists a primary periodicity of 22 years, and the two secondary periodicities of 7 and 4 years. Annual sediment load exists a primary periodicity of 25 years, and a secondary periodicity of 7 years. However, the length of the primary periodicity of runoff showed a decreasing trend during the study period, both the periodicities of sediment load weakened gradually or even disappeared in recent years. Step changes of annual precipitation and runoff in the WRB were occurred in 1984, 1994 and 2004, while for annual sediment load were occurred in 1984, 1994 and 2000. The relationships of precipitation-runoff and runoff-sediment load were also observed to be changed in varying degrees.

(2) We extend methods on previous studies by incorporating the result of attribution analysis of the runoff change in the attribution analysis of river sediment load change, which provides a new perspective for related research. Quantitative assessment revealed that climate variability contributes 71.5% ~ 85.6% changes of mean annual runoff in 1985–1994, 1995–2004 and 2005–2016, with reference to the baseline period of

1970–1984, while human activities play a secondary role. In contrary, human activities (e.g. soil and water conservation, afforestation, construction of water reservoirs) dominate the reduction of river sediment load in the three periods, and the contribution rate ranged in 67.2% ~ 107.5%.

(3) The construction of cascade hydropower stations in the WRB was fundamentally responsible for the significant decreasing trend and the weakened periodicity of sediment load as well as the changed runoff-sediment load relationship at Wulong station in recent years. However, this influence was not big enough to modify the regime of annual runoff in the WRB.

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Credit Author Statement

Xuchun Ye: Conceptualization, Investigation, Writing - Original Draft.

Chong-Yu Xu: Validation, Writing- Reviewing and Editing.

Zengxin Zhang: Software, Resources.

Declaration of Interest Statement：

The authors declared that they have no conflicts of interest to this work.

Cover letter

Dear Editor,

We thank the referees for their additional comments in the second round of review, which have been a great help in improving the quality of our paper. We carefully revised the paper according to these comments and suggestions. The related parts of the paper have been rewritten and improved, and for your easy reading and evaluation, the changed parts are marked using RED COLORED text in the revised version.

We hope the revised version is to your satisfaction, and of course, we are more than happy to improve the paper again according to new comments and suggestions they might come.

Thank you in advance for your considerations.

Sincerely Yours

Xuchun Ye

on behalf of the co-authors,

Figure 1

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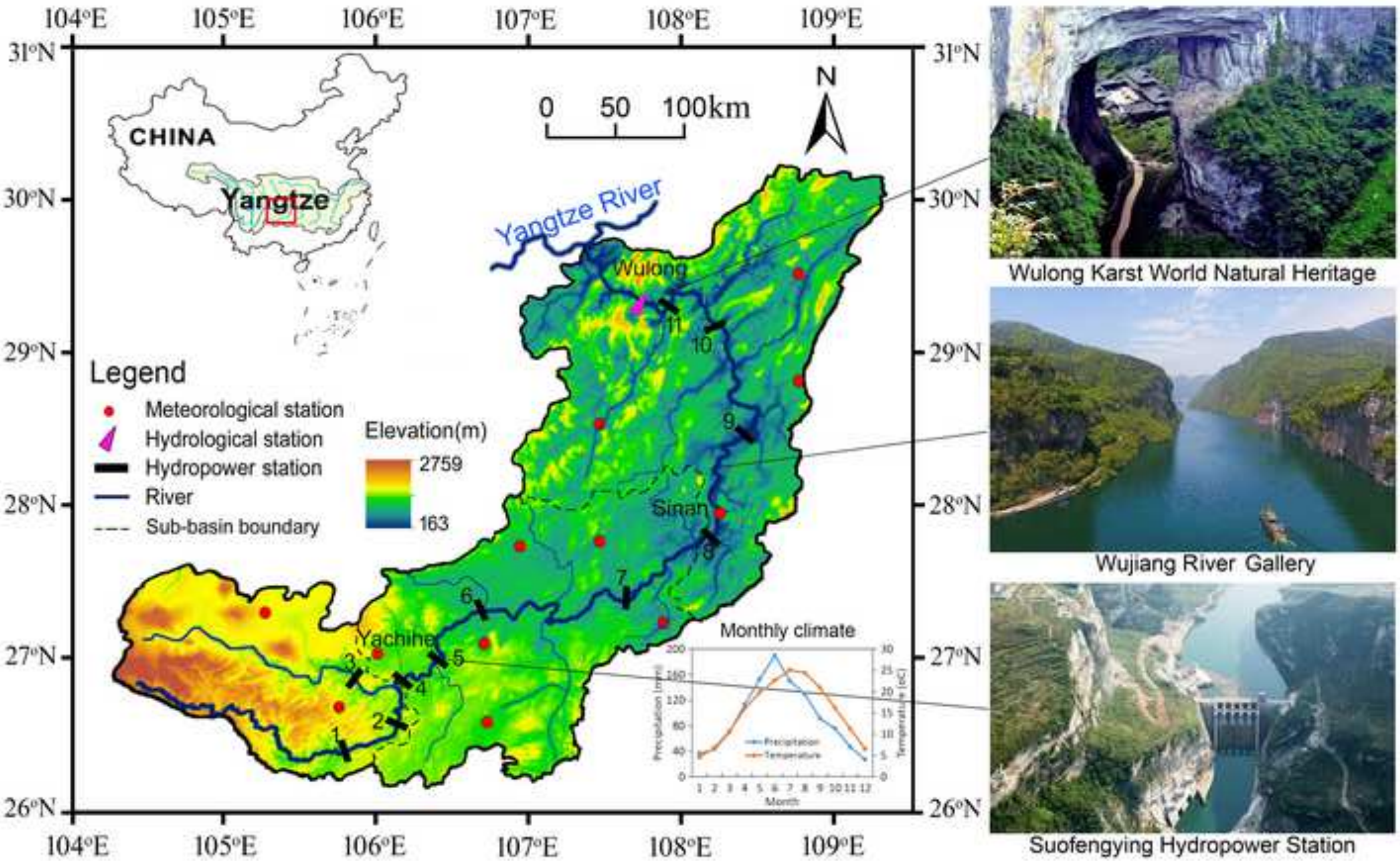

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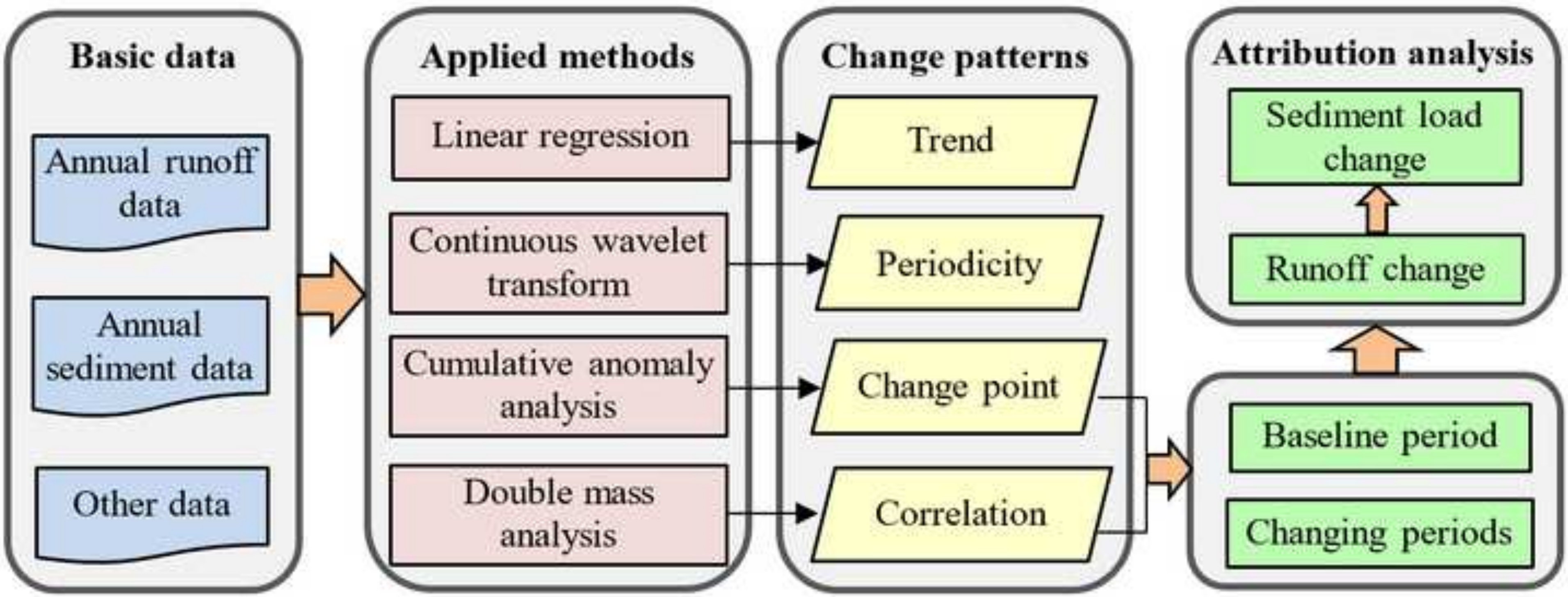

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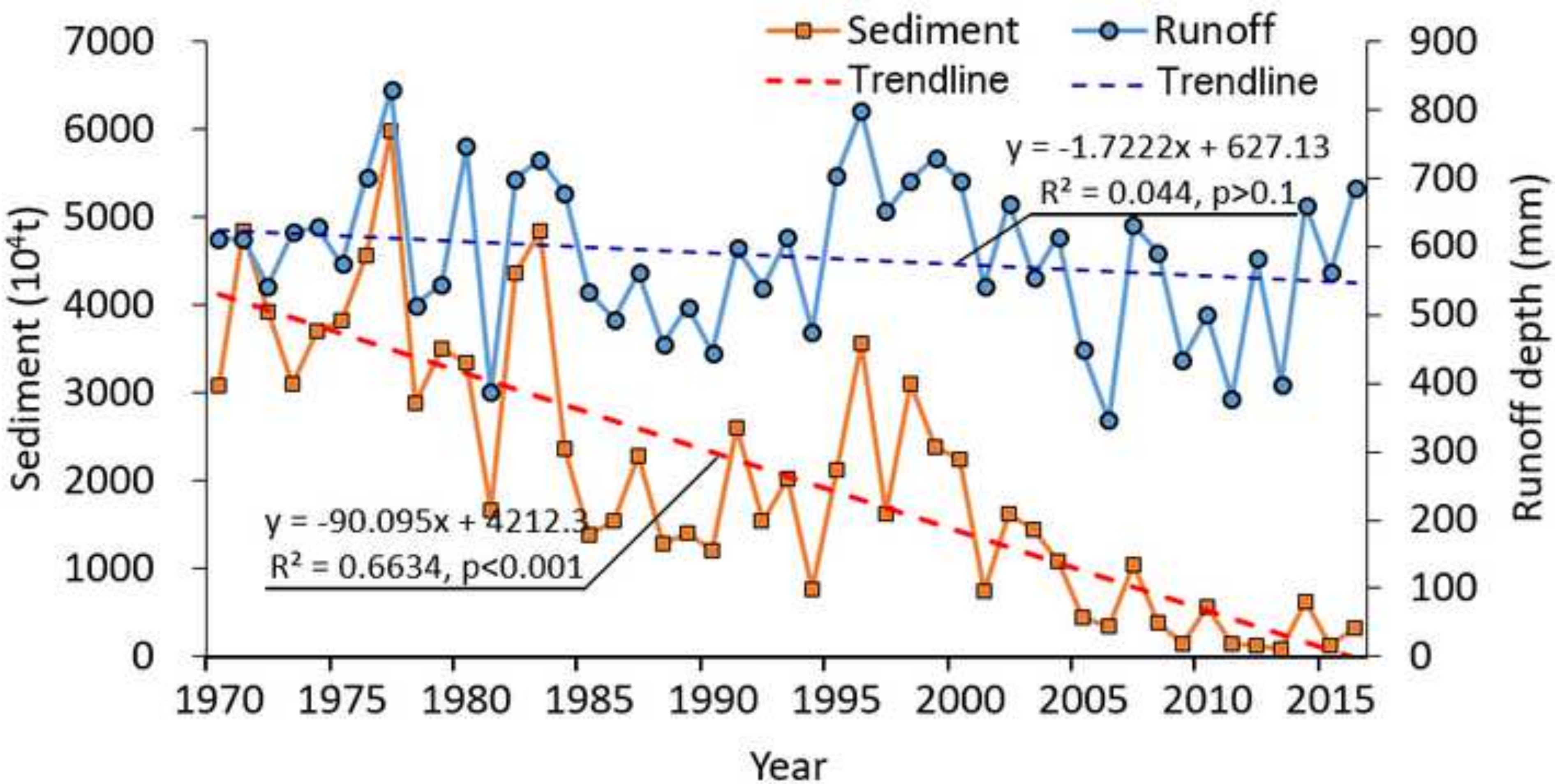

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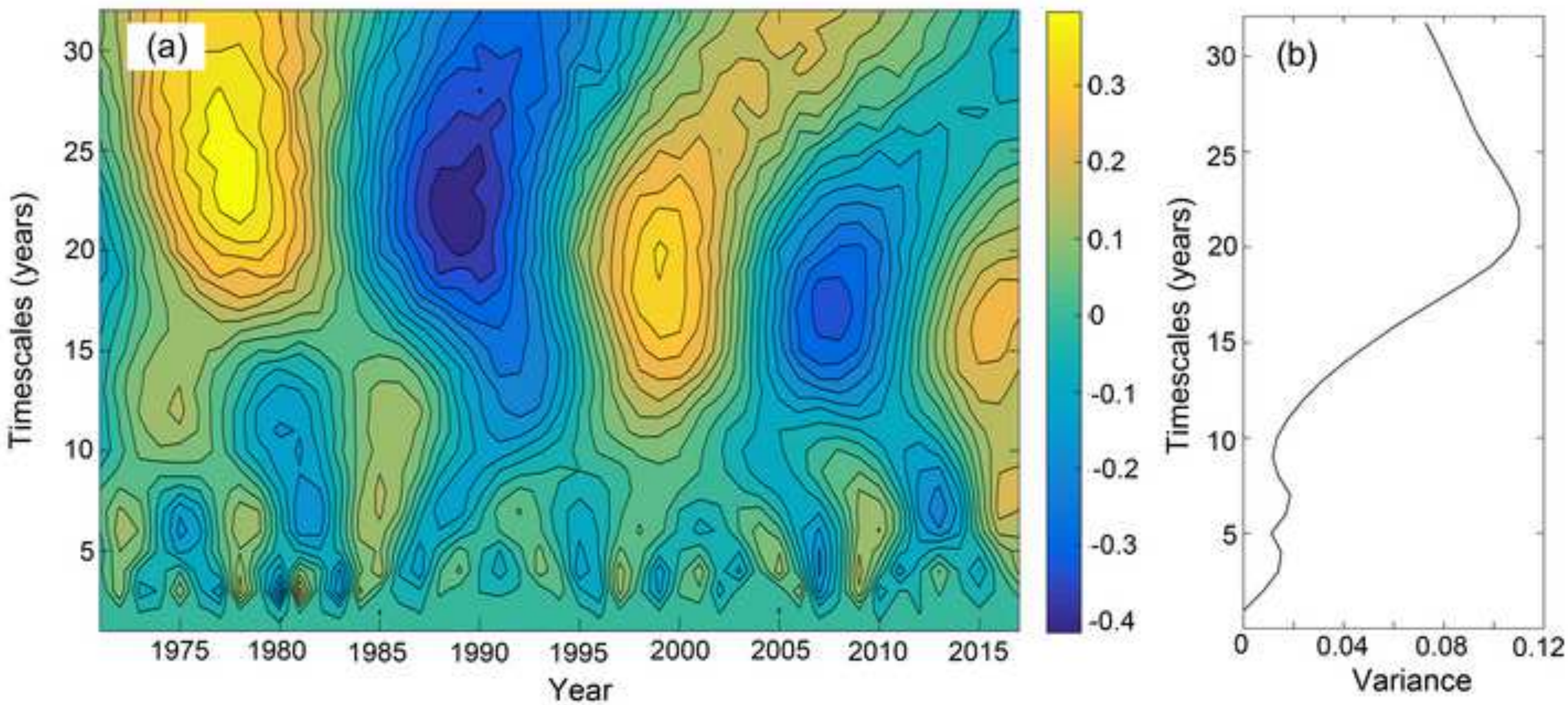

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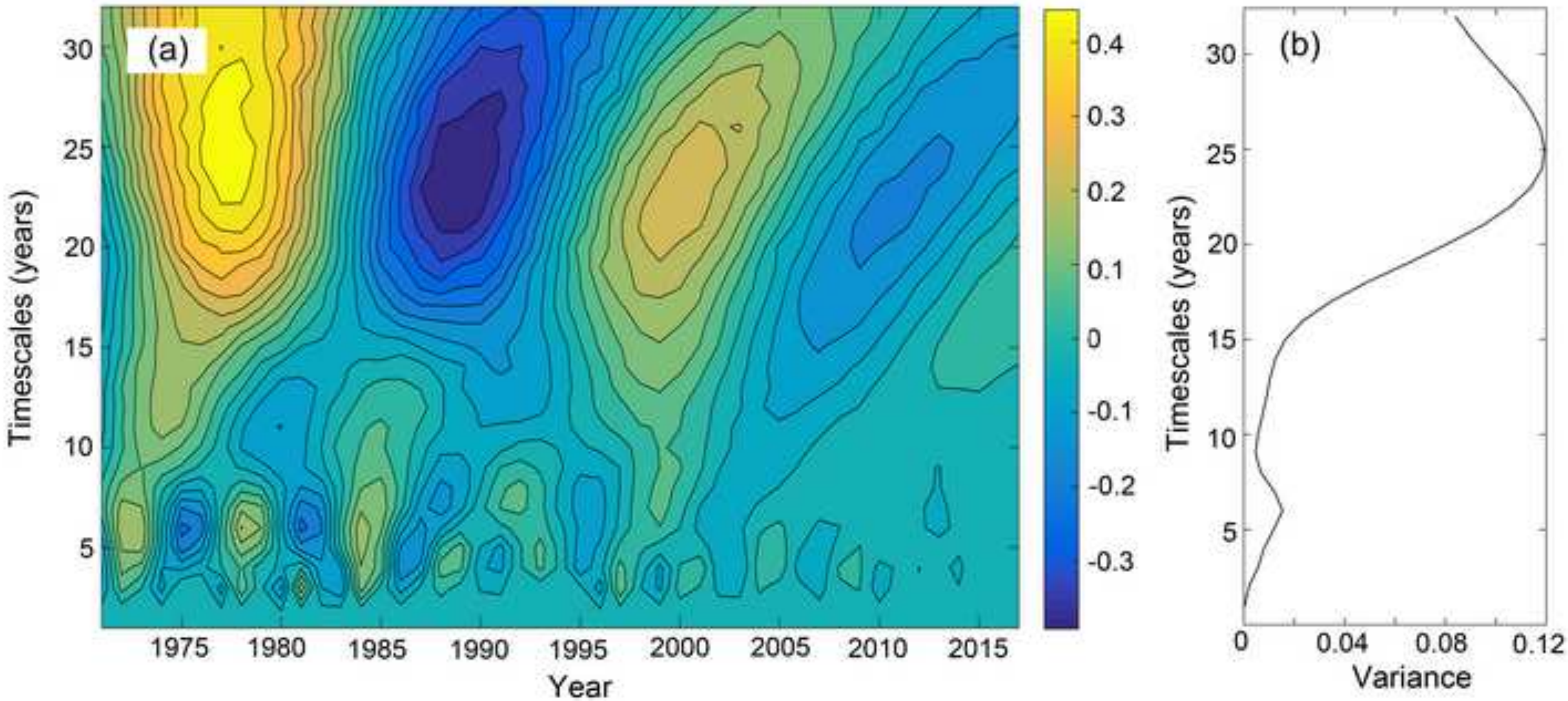

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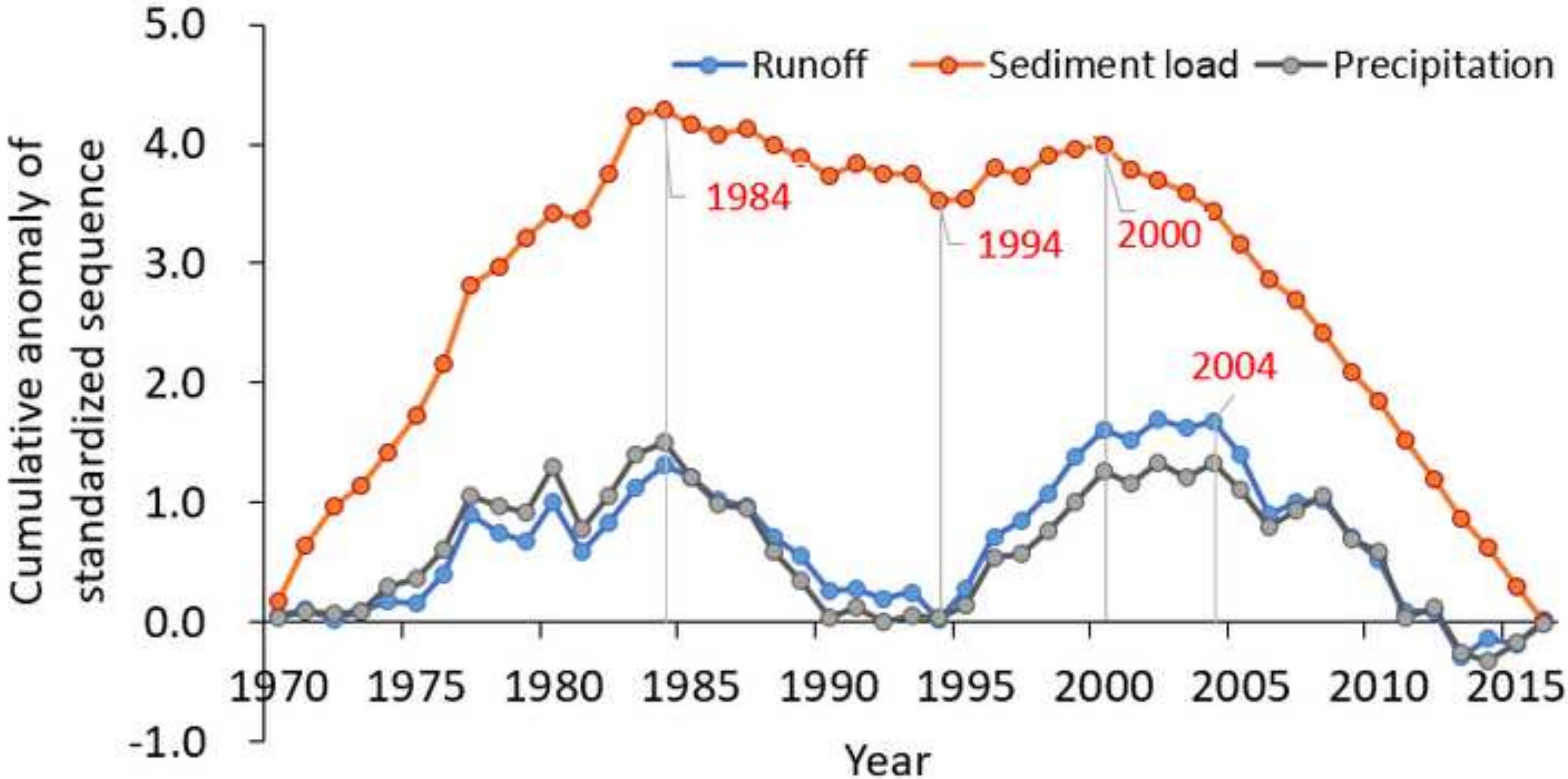

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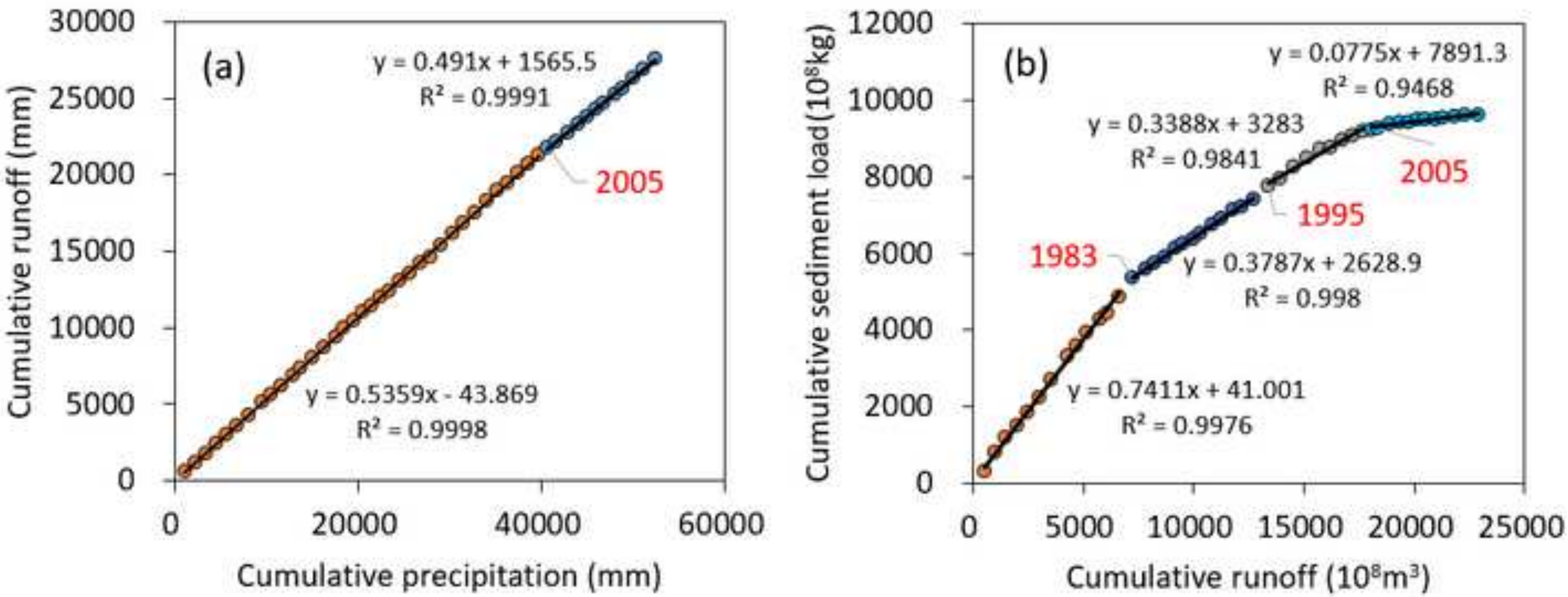

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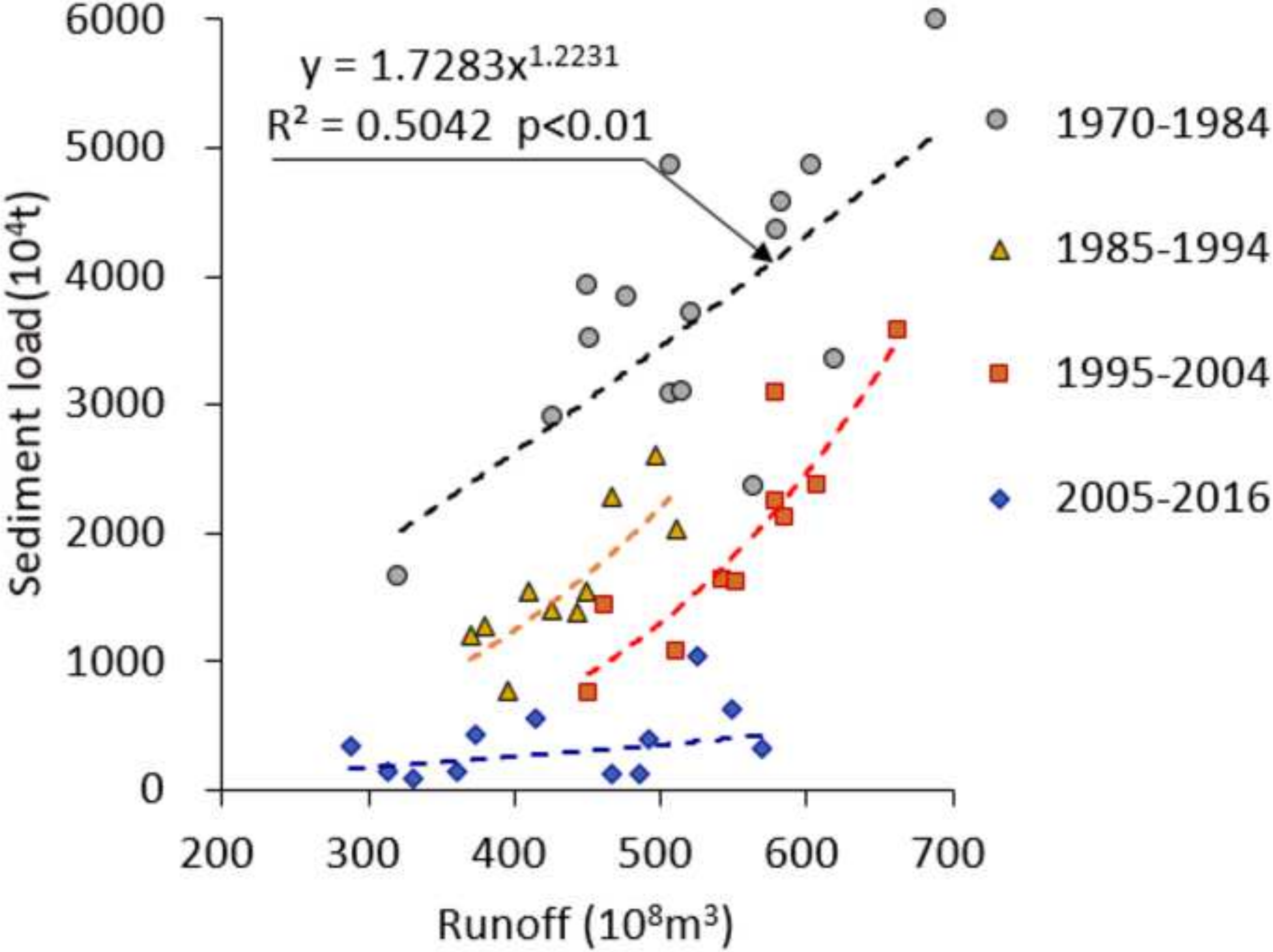

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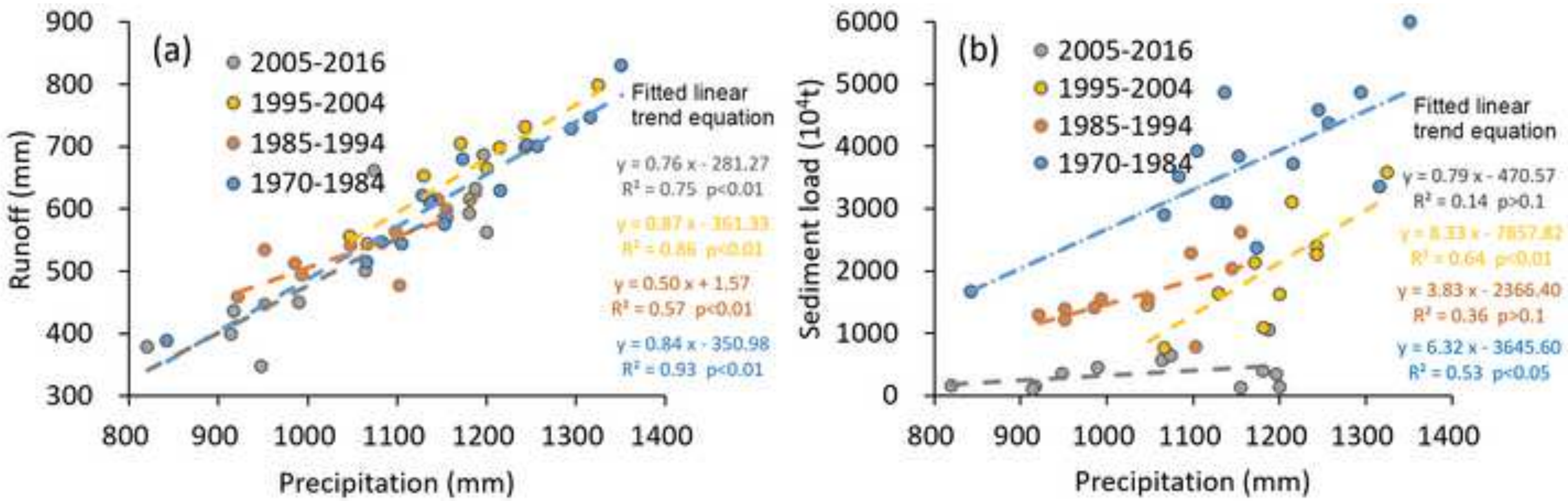

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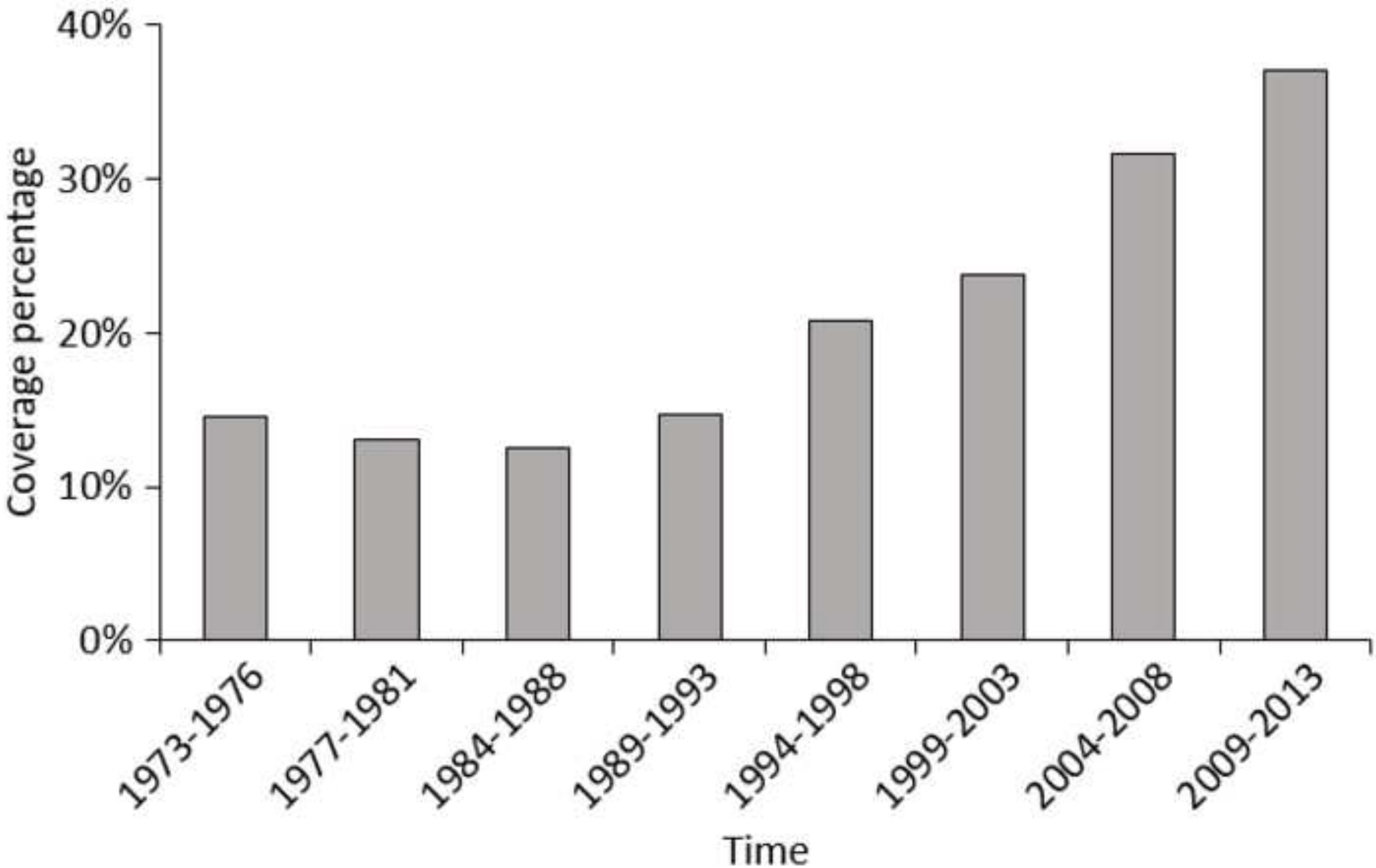

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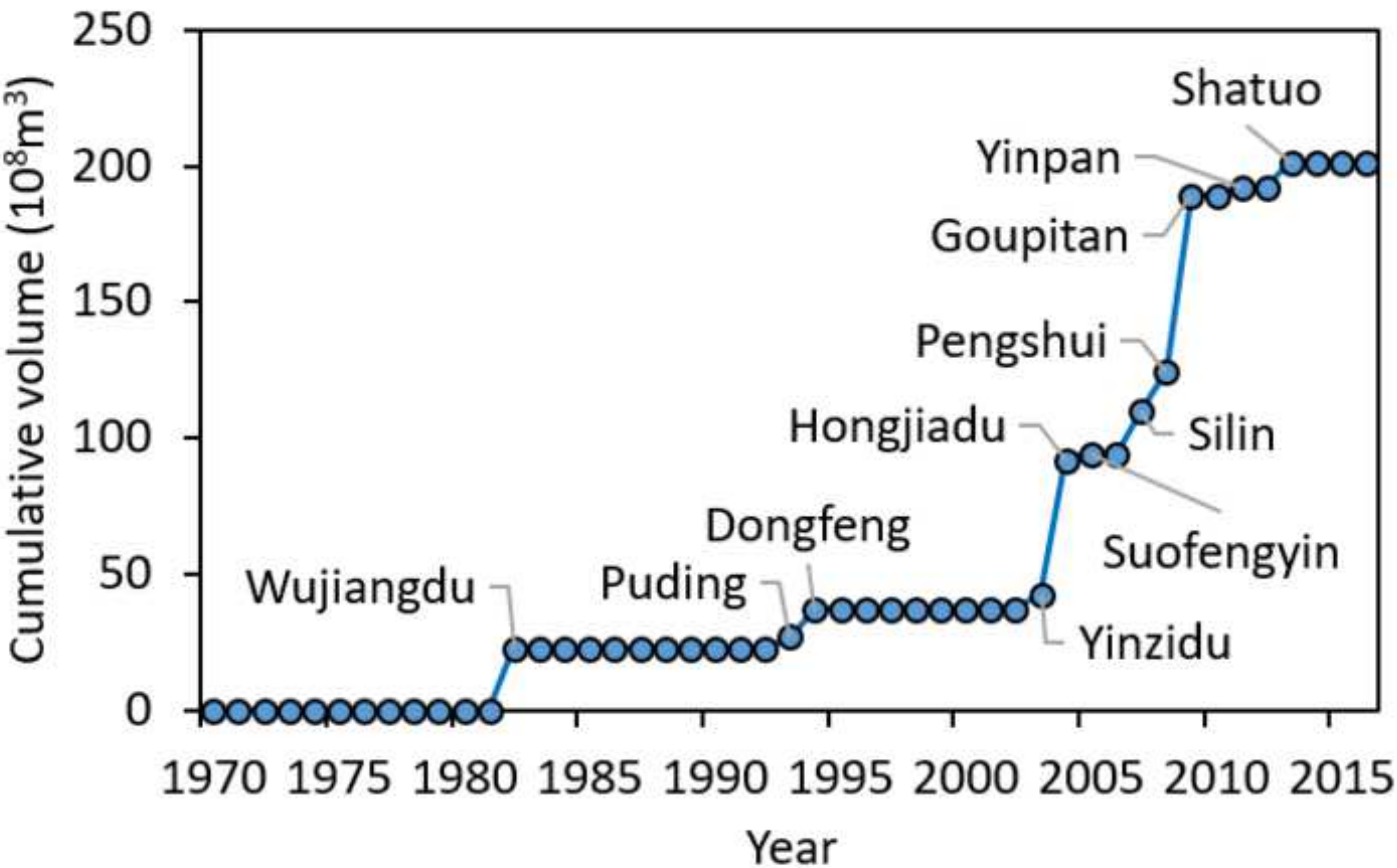

Table 1

Table 1 Average annual runoff and sediment at Wulong station in four periods

Periods	R (mm)	S (10^4t)	α (-)	Cs (mg/L)
1970–1984	628.03	3734.00	0.538	716
1985–1994	523.28	1604.00	0.505	369
1995–2004	665.66	1994.00	0.562	361
2005–2016	518.53	363.33	0.491	84

Note: "R" is mean annual runoff depth, "S" is mean average annual sediment load, "α" is runoff coefficient and "Cs" is sediment concentration.

Table 2 Impacts of climate variability and human activities on runoff change in the WRB

Periods	R (mm/a)	P (mm/a)	ET_p (mm/a)	ΔR (mm/a)	ΔR_{clim} (mm/a)	ΔR_{hum} (mm/a)	$\eta_{clim\text{-}R}$ (%)	$\eta_{hum\text{-}R}$ (%)
1970–1984	628.03	1167.83	1009.97					
1985–1994	523.28	1035.97	991.51	-104.75	-89.64	-15.12	85.6	14.4
1995–2004	665.66	1183.07	955.00	37.63	26.92	10.71	71.6	28.4
2005–2016	518.53	1054.73	998.97	-109.63	-78.28	-31.22	71.5	28.5

Note: R, P, ET_p are mean annual runoff depth, precipitation and potential evaporation, respectively during the period; ΔR is the change in mean runoff with reference to the baseline period; ΔR_{clim} and ΔR_{hum} are the changes in mean annual runoff due to climate change and human activities as estimated using Equation (3) and Equation (6); $\eta_{clim\text{-}R}$ and $\eta_{hum\text{-}R}$ are the relative contribution rates of climate variability and human activities to runoff change as estimated using Equation (7) and Equation (8).

Table 3 Impacts of climate variability and human activities on sediment change in the WRB

Periods	S (10^4t/a)	$S_{sim\text{-}c}$ (10^4t/a)	ΔS (10^4t/a)	ΔS_R (10^4t/a)	ΔS_{clim} (10^4t/a)	ΔS_{hum} (10^4t/a)	$\eta_{clim\text{-}S}$ (%)	$\eta_{hum\text{-}S}$ (%)
1970-1984	3734.00	3655.04						
1985-1994	1604.00	2916.77	-2130.00	-817.23	-699.31	-1430.69	32.8	67.2
1995-2004	1994.00	3916.06	-1740.00	182.06	130.26	-1870.26	-7.5	107.5
2005-2016	363.33	2898.53	-3370.67	-835.47	-597.28	-2773.39	17.7	82.3

Note: S is the observed mean annual sediment; $S_{sim\text{-}c}$ is the re-constructed mean annual sediment load as estimated using Equation (10); ΔS is the change in mean sediment load with reference to the baseline period; ΔS_R is the change in mean sediment load caused by runoff change as estimated using Equation (12); ΔS_{clim} and ΔS_{hum} are the changes in mean annual sediment load due to climate change and human activities as estimated using Equation (13) and Equation (14); $\eta_{clim\text{-}R}$ and $\eta_{hum\text{-}R}$ are the relative contribution rates of climate variability and human activities to sediment load change as estimated using Equation (15) and Equation (16).

Figure caption:

Fig. 1. Topography and river networks of the Wujiang River basin, with hydrological stations and meteorological stations are marked. The photos in the right column shows the typical landscapes of the river basin. Hydropower stations in the Figure are: 1 Puding; 2 Yinzidu; 3 Hongjiadu; 4 Dongfeng; 5 Suofengying; 6 Wujiangdu; 7 Goupitan; 8 Silin; 9 Shatuo; 10 Pengshui; 11 Yinpan.

Fig. 2. Flowchart of the method to assess the impacts of climate variability and human activities on runoff and sediment load changes.

Fig. 3. Annual runoff depth and sediment load of Wulong station during 1970–2016.

Fig. 4. Periodicity distribution of Wulong annual runoff based on Morlet wavelet analysis: (a) continuous wavelet power spectrum and (b) wavelet variance.

Fig. 5. Periodicity distribution of Wulong annual sediment load based on Morlet wavelet analysis: (a) continuous wavelet power spectrum and (b) wavelet variance.

Fig. 6. Variation of the cumulative anomaly curves of annual precipitation, runoff and sediment load of the Wujiang basin during 1970-2016.

Fig. 7. The double mass curves of (a) cumulative precipitation versus cumulative runoff and (b) cumulative runoff versus cumulative sediment load of the Wujiang basin.

Fig. 8. Relationship between annual runoff and sediment load in different periods.

Fig. 9. Linear relationship between (a) precipitation and runoff and (b) precipitation and sediment load of the Wulong station.

Fig. 10. Changes of area percentage of forest coverage in the Guizhou Province.

Fig. 11. Variation of cumulative reservoir volume according to the operation of major hydropower stations in the WRB.

Meteorological data

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Annual runoff and sediment load

Forest coverage of Guizhou Province

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