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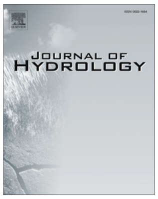

Research papers

Quantifying the impacts of climate and human activities on water and sediment discharge in a karst region of southwest China

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ABSTRACT

Quantifying the impacts of climate and human activities on water and sediment discharge has become a central topic in climate and hydrologic research. This issue, however, has so far received little attention in karst regions around the world. Seven karst catchments located in southwest China were chosen to explore water and sediment discharge responses to different driving factors during the period from the 1950s to 2011. The non-parametric Mann-Kendall test was used to detect both the trends and abrupt changes in water and sediment discharge. The double mass curve method was used to quantify the effects of climate and human activities on water and sediment discharge. Results indicated that the annual water discharge showed a decreasing trend in all catchments (-0.21 to $-3.68 \times 10^8\ \mathrm{m^3\,yr^{-1}}$), and the sediment discharge exhibited a significant decreasing trend (-7 to $-101 \times 10^4\ \mathrm{t\,yr^{-1}}$) for six out of the seven catchments. A rapid decline (abrupt change) in sediment discharge occurred since 2000 for all except Liujiang catchment where the sediment discharge has a slight increase since 1983 as no large dams were constructed in this catchment. Specifically, the magnitude of reduction in sediment discharge (%) significantly increases with the extent of flow regulation as measured by the ratio of the area upstream the dam to the total catchment area for the seven catchments ($R^2 = 0.98$, $P < 0.01$). This study demonstrated that water discharge was mainly influenced by precipitation, while sediment discharge was mainly influenced by human activities (relative contribution 70–111%, regardless of whether the effect is negative or positive). Ecological restoration played somehow important roles in the decrease in sediment discharge (negative relationships of sediment discharge with the Normalized Differential Vegetation Index (NDVI)), but dam construction was likely to be the principal cause of the significant decrease in sediment discharge. This study is of use for better catchment management in karst regions in southwest of China.

1. Introduction

Water and sediment discharge considerably influence the fluvial geomorphology, alluvial plains and deltas through time and space, supporting the riverine ecosystems along adjoining fluvial surfaces (Hupp and Osterkamp, 1996; Lu and Higgitt, 1999; Chen et al., 2001; Zhang et al., 2006). A better understanding of the water and sediment discharge changes and their potential driving forces are thus of paramount importance to effectively utilize water resources and reasonably manage river flows. Generally, climate change and human activities are identified as the two primary causes for changes in water and sediment discharge (Barnett et al., 2008; Wang and Hejazi, 2011; Gao et al., 2013). In recent decades, global climate variability has accelerated the hydrological cycle, and hence changed the spatiotemporal variations of precipitation (Allen and Ingram, 2002; Zhao et al., 2015). This phenomenon has resulted in an increased occurrence of the extreme rainfall events and probably triggers more frequent occurrences of extreme floods in many rivers of the world (Easterling et al., 2000). Sediment transport capacity would increase with an increase in water discharge (Zhang et al., 2009; Li et al., 2015). Thus, precipitation controls water discharge as well as soil erosion and sediment transport (Yang et al., 2015).

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Human activities, such as land use change, dam construction and reservoir operation, are also closely related to water and sediment discharge (Naik and Jay, 2011; Wang and Hejazi, 2011; Wu et al., 2012; Wang et al., 2013; Zhao et al., 2015). Land use change can influence the water balance of a catchment by altering rainfall interception and actual evapotranspiration (Zhang et al., 2008b). It also affects sediment discharge, as land with permanent vegetation cover (forest, shrub, or grassland) typically has lower soil losses than an cropping land (García-Ruiz, 2010; Li et al., 2015). Over the past several decades, land use change has caused a long-term increase in sediment discharge in some rivers (Saito et al., 2001; Tamura et al., 2009), whereas in recent years the dam construction have led to sharp decreases in sediment discharge of many rivers (Nilsson et al., 2005; Syvitski et al., 2005). Dams produced a hydrologic regime that differs significantly from the natural flow regime prior to impoundment, and generated great changes in time, magnitude, and frequency of low and high river flows (Magilligan and Nislow, 2005; Syvitski et al., 2009). Dams not only affect water discharge but also trap large quantities of sediments due to the reduced sediment transport capacity in reservoir areas. It has been reported that over 70% of the world's rivers are intercepted by large dams, and at least one-half of the river sediment may have been trapped in human-made dams and reservoirs (Kummu and Varis, 2007; Zahar et al., 2008).

Recently, the response of water and sediment discharge to changing climate and human activities are well documented (Syvitski et al., 2005; Liquete et al., 2009; Xu et al., 2013a). Furthermore, separation and quantification of the two driving forces on water and sediment discharge have become topical issues in hydrology, garnering considerable concerns (Naik and Jay, 2011; Wu et al., 2012; Gao et al., 2013; Xu et al., 2013b; Yang et al., 2015). In the Yellow River, for example, both water and sediment discharge have shown progressive decline during the past 50 years, which is partly due to climate change (especially precipitation) and more importantly, due to human activities (Milliman, 1997; Miao et al., 2011; Wang et al., 2015). Similarly, the annual water and sediment discharge also exhibited a decreasing trend over the last decades in the Yangtze River. This reduction in water discharge is mainly controlled by variations in precipitation (72%), while human activities contributed 86% of the reduction in sediment discharge (Zhao et al., 2015). In the Colorado and Nile Rivers, human activities (particular dam construction) lead to almost total elimination of riverine sediment discharge (Vörösmarty et al., 2003). However, previous studies focused solely on the non-karst areas and the impact of climate change and human activities on water and sediment discharge is not yet fully understood in karst regions.

In southwest China, the karst area covers nearly 4.26×10^5 km^2 with a population of about 100 million. This region, as one of the largest contiguous karst region in the world, generally demonstrates a different characteristic from non-karst area due to its special geological condition. It is characterized by a complex network of soil pockets, rock matrix, and flow paths of variable hydraulic conductivity (Fu et al., 2015). Unlike the Edwards Plateau karst or Mediterranean karst, this area has relatively steep terrains with the slope of most of the catchment areas greater than 20%. In particular, the special geological condition, unfavorable land use practices, and abundant rainfall cause severe soil erosion and karst rocky desertification in this region (Zhang et al., 2014). At the end of 2005, rock desertification occupies nearly 29% of the karst area in southwest China and has seriously threatened the productivity of agriculture and sustainability of the ecosystem (Feng et al., 2014). To control such severe soil erosion and karst rocky desertification, a number of soil conservation measures have been implemented in this region, including dam and reservoir construction, conversion of cropland into woodland, and vegetation restoration. These human activities may significantly reduce the water and sediment discharge. Nevertheless, there were few attempts at partitioning the effect of climate change and human activities on water and sediment discharge in karst regions.

In this study, seven catchments within the karst area of southwest China were selected to quantify the impacts of climate change and human activities on water and sediment discharge since the 1950s. The objectives of this study are (1) to statistically detect both trends and change points in annual water and sediment discharge and (2) to explore the contributions of climate change and human activities to water and sediment discharge variability.

2. Study area and data

2.1. Study area

The study area is located in the Xijiang basin where the typical karst landform is widespread. The Xijiang River is the largest tributary of the Pearl River, which ranks second (after the Yangtze River) in terms of water discharge and third (after the Yellow and Yangtze rivers) in terms of sediment discharge in China. The Xijiang basin (21°36′17″–27°00′21″N, 102°16′52″–113°23′51″E) has a drainage area of 3.5×10^5 km^2 and the altitude ranging from 0 to 2866 m (Fig. 1). This region experiences a subtropical and tropical monsoon climate straddling the Tropic of Cancer, with the mean annual temperature and precipitation of 18 °C and 1470 mm, respectively. About 43.5% of this region is karst area, which is underlain by soluble carbonate rocks (Fig. 2a). The typical karst landform and the geomorphology are vulnerable to soil erosion due to its fragility. The mean annual water and sediment discharge of the Xijiang River are 2.28×10^{11} m^3 yr^{-1} and 6.45×10^7 t yr^{-1}, respectively. To control soil erosion and for hydro-power generation, a large number of reservoirs have been constructed since the 1960s. The major reservoirs are shown in Fig. 1.

Seven nested catchments (Nanpan, Liujiang, Yujiang, Hongshui, Xunjiang, Wuzhou, and Xijiang) were selected in the Xijiang basin. To clearly describe these seven nested catchments, they were labelled as No. 1 to No. 7 catchments. As shown in Fig. 1, the No. 1, No. 2, and No. 3 catchment refer to Nanpan, Liujiang, and Yujiang catchment, respectively. Hongshui catchment contains Liujiang and No. 4 catchment; Xunjiang catchment contains Liujiang, Hongshui, and No. 5 catchment; and Wuzhou catchment contains Xunjiang and No. 6 catchment. These catchments are corresponding to seven hydrological stations (five on the main channel and two on the tributary) (Table 1; Fig. 1). The catchment boundary was extracted from digital elevation model (DEM) with a resolution of 30 m for the calculation of catchment-averaged hydro-climatic and land condition variables. The detailed information on the precipitation, water and sediment discharge in seven catchments are showed in Table 1. The mean annual Normalized Difference Vegetation Index (NDVI) for the seven catchments are 0.53–0.77 (1982–2011) (Fig. 2b).

2.2. Data

Precipitation (1950s–2011) data at 32 gauging stations in the Xijiang basin were provided by the China Administration of Meteorology (Table 1). The precipitation data were spatially averaged across the study area by the CoKriging interpolation algorithm using ArcGIS software to calculate the catchment-averaged precipitation. Hydrological data series (1950s–2011) of the annual water and sediment discharge extracted from seven hydrological stations in the Xijiang basin were obtained from the hydrological yearbooks of the People's Republic of China (Table 1). The homogeneity and reliability of the data have been checked and firmly controlled before the data were released. The information on reservoirs in

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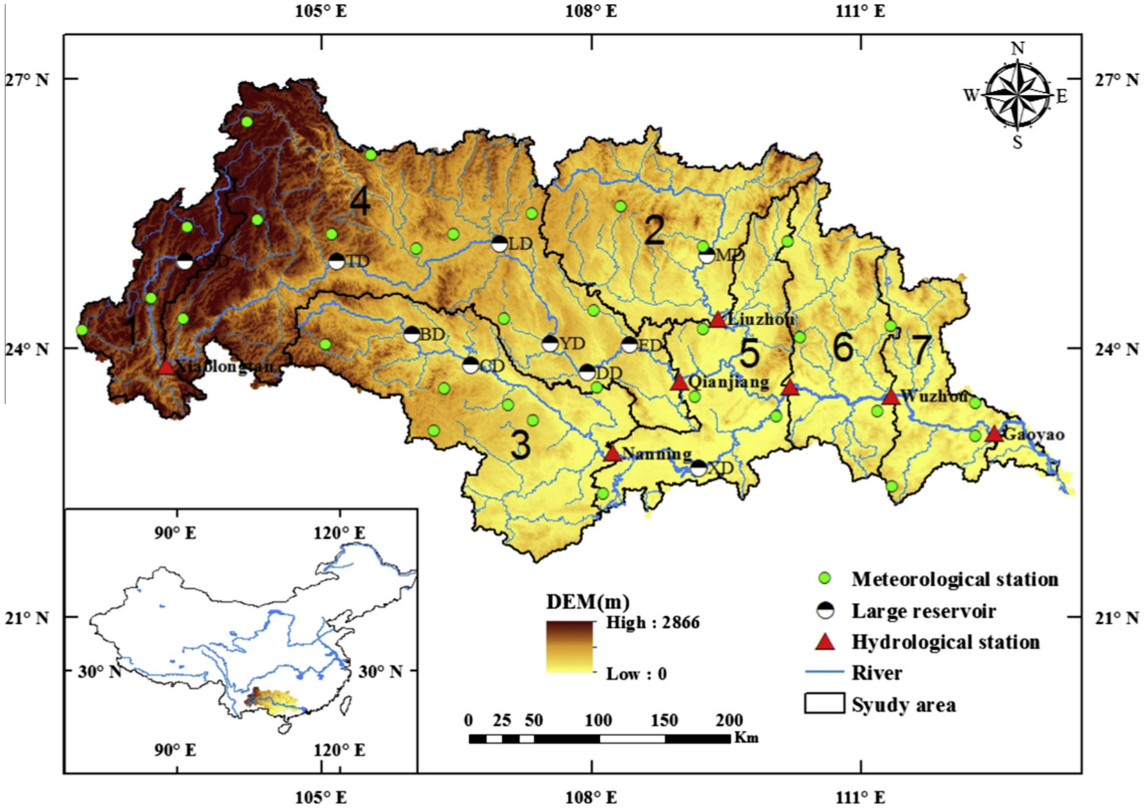

Fig. 1. Locations of meteorological stations, reservoirs, hydrological stations, and seven catchments in a karst area of southwest China. The black lines depict the boundary of each catchment. The definitions of dam abbreviations can be referred to Table 2.

the region extracted from the literature (Dai et al., 2008; Wu et al., 2012) is provided in Tables 2 and 3. The five 1:100,000-scale land-use databases of the late 1980s, 1995, 2000, 2005, and 2010 were obtained from the Resource and Environmental Science Data Center, Chinese Academy of Sciences [http://www.resdc.cn/] (Liu et al., 2014a,b). The NDVI data (1982–2011) was derived from the Land Processes Distributed Active Archive Center, National Aeronautics and Space Administration [https://lpdaac.usgs.gov/].

3. Methodology

The rank-based Mann-Kendall test (M-K) originally proposed by Mann (1945) and later reformulated by Kendall (1975), is widely used to determine the significance of the trends and the change points in hydroclimatic time series (Miao et al., 2010). This method is highly recommended for general use throughout the world due to its robustness for non-normally distributed and censored data. Thus, in this study, we used the M-K test to identify the trends and change points of annual water and sediment discharge over the last 50 years in 7 selected catchments in southwest China. Double mass curve is a practical and visual method to quantify the hydrological regime changes due to human disturbances by comparing two contrasting periods before and after the change point years (Gao et al., 2013, 2015). Hence, we used the double mass curve method to evaluate relative importance of climate change and human activities on water and sediment discharge variation for 7 karst catchments.

3.1. Trend test

The rank-based, non-parametric M-K test was used to detect statistically significant trends in water and sediment discharge (Mann, 1945; Kendall, 1975). For a given time series $X = x_1, x_2, \ldots, x_n$, the M-K test for a monotonic trend is defined as follows:

$$Z = \begin{cases} (S-1)/\sqrt{Var(S)} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ (S+1)/\sqrt{Var(S)} & \text{if } S < 0 \end{cases} \tag{1}$$

where $$S = \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \tag{2}$$

$$\operatorname{sgn}(x_j - x_i) = \begin{cases} 1 & \text{if } x_j > x_i \\ 0 & \text{if } x_j = x_i \\ -1 & \text{if } x_j < x_i \end{cases} \tag{3}$$

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p-1)(2t_p+5)}{18} \tag{4}$$

in which n is the record length; x_i and x_j are the sequential data values at times i and j ($i < j$), respectively; S is the test statistic; t_p is the number of ties for the pth value; q is the number of tied values; Z is the standardized test statistic value. The null hypothesis of no trend is rejected at the significance level of α if $|Z| > Z_{(1-\alpha/2)}$, where α is the significance level of the test and $Z_{(1-\alpha/2)}$ refers to the critical value of the standard normal distribution with a probability exceeding $\alpha/2$. In this study, the significant level of $\alpha = 5\%$ was used. A positive value of Z represents an upward trend, while a negative Z value indicates a negative trend. The magnitude of the trend is given as:

$$Slope = \text{Median}\left[\frac{x_j - x_i}{j - i}\right] \tag{5}$$

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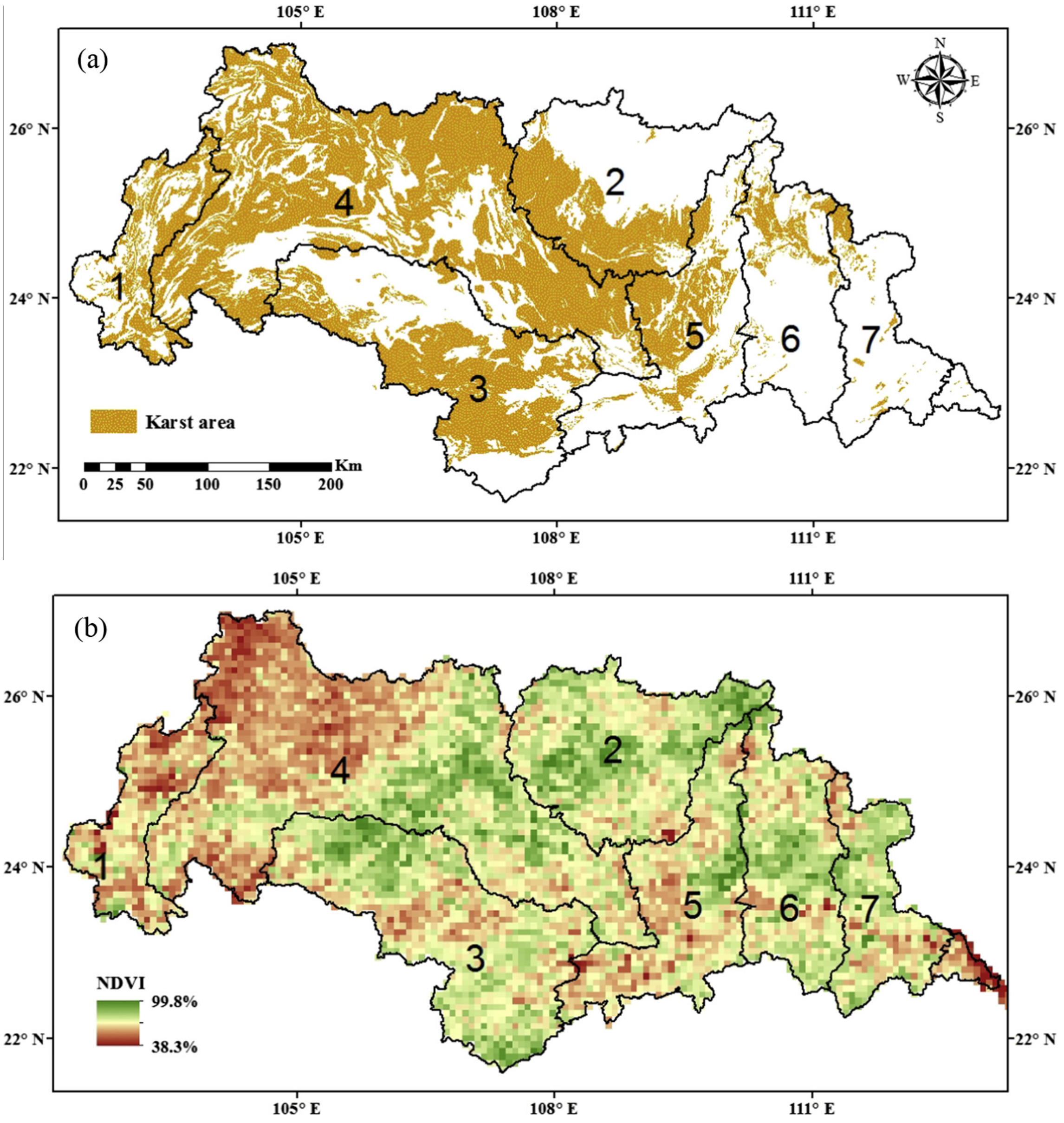

Fig. 2. Spatial distribution of: (a) carbonate rock (karst area); and (b) normalized differential vegetation index (NDVI, 1982–2011) in the studied area.

Table 1
Descriptive statistics of precipitation, water and sediment discharge for seven catchments in southwest of China.

Catchment	Gauge station	Area (10^4 km^2)	Karst coverage (%)	Precipitation			Water discharge			Sediment discharge		
				Mean (mm yr^{-1})	Cv (%)	Period	Mean (10^8 m^3 yr^c)	Cv (%)	Period	Mean (10^4 t yr)	Cv (%)	Period
Nanpan	Xiaolongtan	1.54	51	926	16	1953–2011	37.1	37	1953–2011	463.3	55	1964–2011
Liujiang	Liuzhou	4.54	39	1379	13	1954–2011	392.6	22	1954–2011	513.3	69	1955–2011
Yujiang	Nanning	7.27	42	1207	13	1954–2011	368.9	27	1954–2011	844.3	60	1954–2011
Hongshui	Qianjiang	12.89	64	1194	11	1954–2011	653.1	21	1954–2011	3772	74	1954–2011
Xunjiang	Dahuangjiangkou	28.85	51	1257	11	1955–2011	1699	19	1955–2011	5239	54	1955–2011
Wuzhou	Wuzhou	32.70	47	1283	11	1955–2011	2011	19	1955–2011	5841	53	1955–2011
Xijiang	Gaoyao	35.15	44	1309	10	1957–2011	2173	21	1957–2011	6267	48	1957–2011

Note: Cv refers to the coefficient of variation.

in which *Slope* is the median of all possible combinations of pairs for entire data set. A positive *Slope* value denotes a positive trend and a negative *Slope* value denotes a negative trend.

The M-K test, however, is strongly influenced by autocorrelation or serial correlation within the time series. Thus, before the M-K test was applied, the water and sediment discharge

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Table 2
Summary information of major dams in study area.

ID	Reservoir	Initial operated (year)	Regulated area (10^4 km^2)	Height (m)	Storage capacity (km^3)
XD	Xijin	1964	7.73	51	1.4
CD	Chengbihe	1966	0.21	70	1.2
MD	Mashi	1971	0.20	34	0.3
ED	Etan	1981	11.8	63	1.0
DD	Dahua	1982	11.2	75	1.0
YD	Yantan	1992	10.7	110	3.4
TD	Tianshengqiao	1997	5.01	180	10.8
CSD	Chaishitan	2001	0.44	103	0.44
BD	Baise	2006	1.96	130	5.7
LD	Longtan	2006	9.85	192	27.3

Table 3
Identification of the effective dams in each selected catchment.

Catchment	Gauge station	Dams in upstream of gauge station	Relatively regulated area (%)
Nanpan	Xiaolongtan	CSD	28.6
Liujiang	Liuzhou	MD	4.4
Yujiang	Nanning	CD, BD	29.8
Hongshui	Qianjiang	ED, DD, YD, TD, LD	91.5
Xunjiang	Dahuangjiangkou	XD, CD, ED, DD, YD, TD, BD, LD	68.4
Wuzhou	Wuzhou	XD, CD, ED, DD, YD, TD, BD, LD	60.3
Xijiang	Gaoyao	XD, CD, ED, DD, YD, TD, BD, LD	56.1

Note: Abbreviations for the dams are listed in Table 2. Relatively regulated area refers to the dam controlled area to the corresponding catchment area.

series were checked for autocorrelation using the following equation:

$$r_k = \frac{Cov(x_i, x_{i+k})}{Var(x_i)} = \frac{\frac{1}{n-k}\sum_{i=1}^{n-k}(x_i - \bar{x})(x_{i+k} - \bar{x})}{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{6}$$

where r_k is autocorrelation coefficient; k is the number of the lag; x_i ($i = 1, 2, \ldots$) is the tested series; $\bar{x}$ is the mean of the time series. The critical value of r_k for the 95% confidence level is calculated as follows:

$$r_k(95\%) = \frac{-1 \pm \sqrt{n-k-1}}{n-k} \tag{7}$$

To eliminate the effect of serial correlation on M-K test, the trend-free pre-whitening (MK-TFPW) was applied to the water and sediment discharge series with significant autocorrelation (Yue and Wang, 2004).

3.2. Change point analysis

The M-K test method was also used to detect the occurrence of a change point in water and sediment discharge. For a given time series $X = x_1, x_2, \ldots, x_n$, the M-K rank statistic (S_k) is calculated as:

$$S_k = \sum_{i=1}^{k} r_i \quad (2 \leqslant k \leqslant n) \tag{8}$$

$$\text{where} \quad r_i = \begin{cases} 1 & \text{if } x_j > x_i \\ 0 & \text{if } x_j \leqslant x_i \end{cases} \quad (j = 1, 2, 3, \ldots, i) \tag{9}$$

The mean and variance of the test statistic (S_k) are calculated as:

$$E[S_k] = \frac{n(n-1)}{4} \tag{10}$$

$$Var[S_k] = \frac{n(n-1)(2n+5)}{72} \tag{11}$$

The sequential values of the statistic UF_k are then calculated as:

$$UF_k = \frac{S_k - E[S_k]}{Var[S_k]} \tag{12}$$

UF_k is the normally distributed and constitutes a forward sequence curve. Following the same procedure, the retrograde time series $X = x_n, x_{n-1}, \ldots, x_1$ was used to calculate the backward sequence values of the statistic $UB_k = -UF_k$ ($k = n, n-1, \ldots, 1$). Thus, the sequential version of this test is exhibited in a graphical format, displaying curves of the statistics UF_k and UB_k. The UF_k statistic indicates the time evolution of the analyzed series, and the UB_k is plotted to localize the beginning of the change. If the intersection point of the two lines UF_k and UB_k within the confidence interval, a change point occurred (confidence level 95%).

3.3. Double mass curve method

The theory behind the double mass curve method is that a plot of the two cumulative quantities exhibits a straight line for a concurrent period if the proportionality between the two variables is unchanged. A change in the slope of the double mass curve indicates that the original relationship between the two variables was broken. Thus, the double mass curve is a straight line when influenced by only climate variability, whereas the inflection of the curve denotes when human activities began to significantly influence water or sediment discharge.

Based on the change point analysis by M-K test, the period was separated into pre-change (i.e. the human effect is not significant) and the post-change (i.e. greatly affected by climate variability and human activities) periods. In this study, precipitation was used as an index to account for the variation in hydrological records as a result of climate change. Double mass curves of precipitation *vs.* water discharge or precipitation *vs.* sediment discharge were plotted for pre-change and post-change periods to estimate the changes induced by climate variability and human activities, respectively. The information on precipitation *vs.* water or sediment discharge in the pre-change period was used to establish linear regression equations. The mean precipitation of the post-change period was put into these regression equations, and the mean annual water and sediment discharge of post-change period without the effects of human activities were extrapolated. Then the impact of human activities on water or sediment discharge can be calculated as follows:

$$\Delta S_{hum} = S_{ao} - S_{ac} \tag{13}$$

where ΔS_{hum} denotes the change in the mean annual water or sediment discharge due to the effect of human activities, S_{ao} and S_{ac} represent the observed and calculated water or sediment discharge of the post-change period extrapolated using the regression equation for the pre-change period. The amount of impact due to climate variability (ΔS_{clim}) can be determined in the following expression:

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

$$\Delta S = S_{ao} - S_{po} \tag{15}$$

where ΔS refers to the change in observed water or sediment discharge between pre-change and post-change year, where S_{po} is the observed water or sediment discharge of the pre-change period.

4. Results

4.1. Trend analysis

The statistical characteristics of precipitation, water and sediment discharge of the seven catchments since the 1950s are shown in Table 1. The precipitation varied substantially from 926 to 1379 mm among the seven catchments. The mean water and sediment discharge also ranged considerably from 37.1×10^8 to $2173 \times 10^8\ \mathrm{m^3\ yr^{-1}}$ and from 463.3×10^4 to $6267 \times 10^4\ \mathrm{t\ yr^{-1}}$, respectively. According to the classification proposed by Nielsen and Bouma (1985), precipitation, water and sediment discharge all demonstrated moderate variability ($10\% < Cv < 100\%$). In particular, the Cv values of sediment discharge are much higher than those of precipitation (Table 1). This result was probably caused by that soil erosion strongly influenced by several other intrinsic variables such as soil characteristics (e.g., texture, bulk density, and cohesion), plant properties (e.g., coverage, litter, and root), in addition to the extrinsic variables (e.g., climate), resulted in a high degree of spatial heterogeneity in sediment discharge (Knapen et al., 2007; Wei et al., 2007; Li et al., 2015).

The M-K trend tests for the annual precipitation, water and sediment discharge are given in Table 4. Overall, no significant trend was found for the precipitation series in all seven catchments ($P > 0.05$). Water discharge in all seven catchments showed a decreasing trend, but this trend is only significant statistically for the Nanpan catchment ($P < 0.05$). For sediment discharge, significant decreasing trends were detected for six of the seven catchments ($P < 0.05$), except for Liujiang ($P > 0.05$) (Table 3, Fig. S1 of Supplementary Information). Precipitation at most catchments decreased by 0.39–1.65 $\mathrm{mm\ yr^{-1}}$, and showed a positive trend of 0.24 $\mathrm{mm\ yr^{-1}}$ for one catchment only. The change rate of water discharge varied from $-0.21 \times 10^8\ \mathrm{m^3\ yr^{-1}}$ to $-3.69 \times 10^8\ \mathrm{m^3\ yr^{-1}}$. These reductions are equivalent to 0.05–0.62% of the mean annual water discharge given in Table 1. For sediment discharge, the largest reductions were observed in Nanpan, Hongshui, Xunjiang, Wuzhou, and Xijiang catchments with the rate of decrease ranging from $6.96 \times 10^4\ \mathrm{t\ yr^{-1}}$ to $100.96 \times 10^4\ \mathrm{t\ yr^{-1}}$, or equivalent to 1.29–1.85% of the corresponding mean annual sediment discharge. The significant reductions in sediment discharge were probably caused by intensive human activities such as dam construction and soil and water conservation control implementation (Dai et al., 2008; Zhang et al., 2008a; Wu et al., 2012). Nevertheless, the sediment discharge exhibited a gradually increasing trend in Liujiang catchment (Table 3, Fig. S1 of Supplementary Information). There is only one Mashi (MD) dam with a storage capacity of 0.3 $\mathrm{km^3}$ in this catchment (Table 2). In fact, the ratio of MD dam controlled area to the Liujiang catchment area, defined here as the relatively regulated area, is the minimum (4.4%) among the seven catchments (Table 3). Interestingly, the proportional reduction in sediment discharge (%) since the abrupt change time is logarithmically related to the relatively regulated area ($R^2 = 0.98$, $P < 0.01$; Fig. 3). This implied that as the catchment is further regulated with more dams, sediment discharge would be drastically reduced downstream. Hence, the slight increase in sediment discharge in Liujiang catchment is probably related to the fact that no large reservoirs existed in this region (Dai et al., 2008; Wu et al., 2012). Additionally, the rock desertification is quite severe in Liujiang catchment, and this serious ecological problem has a negative effect on plant growth and thus could have led to increased soil erosion and sediment delivery (Zhang et al., 2008a).

4.2. Change point analysis

Based on M-K test, abrupt changes of water and sediment discharge are shown in Table 5. No significant abrupt changes in water discharge were detected for all seven catchments. In contrast, significant abrupt downward changes mostly occurred around 2000 for sediment discharge. This sudden decrease in sediment discharge may be largely attributed to the commission of the Tianshengqiao (TD) dam in 1997, which has a storage capacity of 10.8 $\mathrm{km^3}$ and otherwise sediment discharge of $1.65 \times 10^7\ \mathrm{t\ yr^{-1}}$ was expected from the upper reaches of the Xijiang River. Wu et al. (2012) also indicated that the sediment discharge decreased by $\sim 3 \times 10^7\ \mathrm{t\ yr^{-1}}$ after the closure of the TD dam and the reduction in sediment discharge account for 40% of the Xijiang River. Sediment discharge at Liujiang catchment, however, exhibited a significant abrupt increase in 1983. In the 1980s, the agricultural development and economic reformation in China significantly increased soil erosion (Wu et al., 2012). The limited extent of flow regulation could not effectively reduce sediment generation and delivery in the catchment. The severe rock desertification has overwhelmed the effect of dam construction, resulting in an observed increase in sediment discharge in the Liujiang catchment.

The period prior to an abrupt change in the annual water or sediment discharge is called the pre-change period. Likewise, the post-change period refers the period since the abrupt changes. The differences in the mean water or sediment discharge between the pre-change and post-change periods were also calculated (Table 5). The relative change of the mean water discharge varied from −22% (Hongshui) to 7.5% (Liujiang), while the sediment discharge changed from −86% (Hongshui) to 35% (Liujiang). In general, the reductions in the annual sediment discharge were more dramatic than those in the water discharge. This implied that the effects of the potential factors influencing the water and sediment discharge

Table 4
Summary of the trend analysis for annual precipitation, water and sediment discharge using the Mann-Kendall (M-K) Test.

Catchment	Precipitation		Water discharge		Sediment discharge	
	Slope (β) ($\mathrm{mm\ yr^{-1}}$)	P	Slope (β) ($10^8\ \mathrm{m^3\ yr^{-1}}$)	P	Slope (β) ($10^4\ \mathrm{t\ yr^{-1}}$)	P
Nanpan	−1.40	0.219	−0.23	**0.026**	−6.96	**0.010**
Liujiang	0.24	0.883	−0.21	0.489	0.70	0.756
Yujiang	−0.39	0.748	−0.96	0.182	−7.02	**0.034**
Hongshui	−1.68	0.167	−2.18	0.064	−69.66	**0.000**
Xunjiang	−1.19	0.390	−0.83	0.715	−74.66	**0.003**
Wuzhou	−1.12	0.470	−1.67	0.630	−100.96	**0.000**
Xijiang	−1.65	0.212	−3.68	0.380	−81.02	**0.002**

Note: Bold number indicates significant trends at 95% confidence level.

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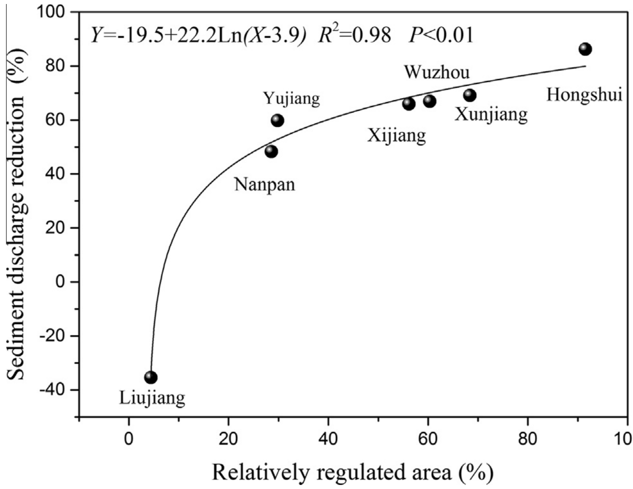

Fig. 3. Relationship between the sediment discharge reduction (%) and relatively regulated area (%) for seven catchments. The sediment discharge reduction refers to the proportional reduction in sediment discharge after abrupt change time. The relatively regulated area refers to ratio of the dam controlled area to its associated catchment area. The black line in plot represents the best fit.

are different (Zhang et al., 2008b; Miao et al., 2010). Consequently, it is essential to explore the impacts of climate variability and human activities on water and sediment discharge.

4.3. Relative importance of climate and human activities on water and sediment discharge

Double mass curves of precipitation *vs.* water discharge, along with the linear regression lines, are shown in Fig. 4. The relationships between cumulative annual precipitation and cumulative water discharge can be expressed with one straight line and no breakpoints were detected, further corroborating the conclusion that no significant abrupt changes have occurred using the M-K test. The double mass curves exhibited the best fit between precipitation and water discharge (R^2 ranging from 0.9971 to 0.9998, Fig. 4). The slope of the double mass curves before and after the abrupt change years was also presented in Fig. 4. As expected, the slopes of the regression lines for the before and after point period were nearly identical. This result indicated that the water discharge was almost all influenced by climate variability, and the effect of human activities on water discharge is minimal for this karst region (Zhang and Lu, 2009; Zhao et al., 2014).

Unlike water discharge, the double mass curves show clear transition points for sediment discharge, which indicated that the variations in sediment discharge were not only affected by precipitation but also by human activities in all seven catchments (Fig. 5). This result further corroborates the results using the M-K test for detecting change points in annual sediment discharge. The slopes of the regression lines obviously decreased after the transition years for six catchments, while an increasing trend was only found for the Liujiang catchment. The largest decrease in the slope of the regression line was detected for the Hongshui catchment (−87%), indicating that soil conservation (e.g. the relatively regulated area; Fig. 3) in this catchment is most effective in reducing sediment discharge. For the Liujiang catchment, the slope of the regression lines increased by 62% and thus this catchment should be paid greater effort in controlling sediment delivery.

Due to no significant abrupt change point and one straight line of the double mass curves for precipitation and water discharge, we consider the water discharge was mainly influenced by precipitation variations (Zhao et al., 2014), and thus only summarizes the relative contributions of climate variability and human activities to the changes in sediment discharge in Table 6. Compared with climate changes, human activities exert a substantial influence on the variation in sediment discharge. In general, the contributions of human activities to sediment discharge reduction is high for six of the seven catchments (−70% to −95%), and these contributions are particularly high for some large catchments (>10^5 km^2) such as Hongshui, Xunjiang, Wuzhou, and Xijiang catchment (−90% to −95%). As noted before, only in Liujiang catchment do human activities have continued to cause the sediment discharge to increase. Additionally, the most significant human impact on sediment discharge is also experienced by Liujiang catchment (+111%). Overall, the impact of human activities far exceeds that of climate change on sediment discharge, no matter whether the effect is negative or positive.

5. Discussion

5.1. Effects of precipitation on water and sediment discharge

Climate oscillations can cause precipitation changes that further affect the annual variations in water and sediment discharge (Zhang et al., 2008a; Zhao et al., 2015). Evidently, the correlations between annual regional precipitation and water discharge are all significant ($P < 0.01$; Table 7), which implied that the precipitation exerted substantial influence on water discharge (Miao et al., 2011; Gao et al., 2015). The relative importance of precipitation and human activities in determining variation of water discharge over time in karst areas is very different from non-karst areas. In non-karst areas, such as Chaobai River (Wang et al., 2009), Tarim River (Tao et al., 2011), Luanhe River (Wang et al., 2013), Weihe River (Guo et al., 2014), and Yellow River basins (Liang et al., 2015), human activities play a dominant role (59–77%) in the reduction of water discharge, whereas the effect of climate change was found to be minor. In some other non-karst areas, such as Columbia River

Table 5
Results of abrupt change analysis for annual water and sediment discharge using the Mann-Kendall (M-K) test.

Catchment	Water discharge				Sediment discharge			
	Change point (yr)	Pre-change (10^8 m^3 yr^{-1})	Post-change (10^8 m^3 yr^{-1})	Chang of mean (%)	Change point	Pre-change (10^4 t yr^{-1})	Post-change (10^4 t yr^{-1})	Chang of mean (%)
Nanpan	1989	40.08	32.99	−17.68	**2002**	508.16	262.66	−48.31
Liujiang	1992	383.64	412.22	7.45	**1983**	421.80	571.15	35.41
Yujiang	2004	380.13	306.16	−19.46	**2002**	920.58	370.22	−59.78
Hongshui	2002	676.04	528.21	−21.87	**1997**	4767.95	655.82	−86.25
Xunjiang	1997	1706.46	1631.88	−4.37	**2000**	6110.73	1886.82	−69.12
Wuzhou	1997	2028.54	1910.36	−5.83	**1997**	7003.43	2317.23	−66.91
Xijiang	1997	2203.63	2027.01	−8.02	**2001**	7149.86	2435.60	−65.94

Note: Pre-change and post-change refer to the average value before and after the abrupt change, respectively; years in bold indicate a significant change at 95% confidence level.

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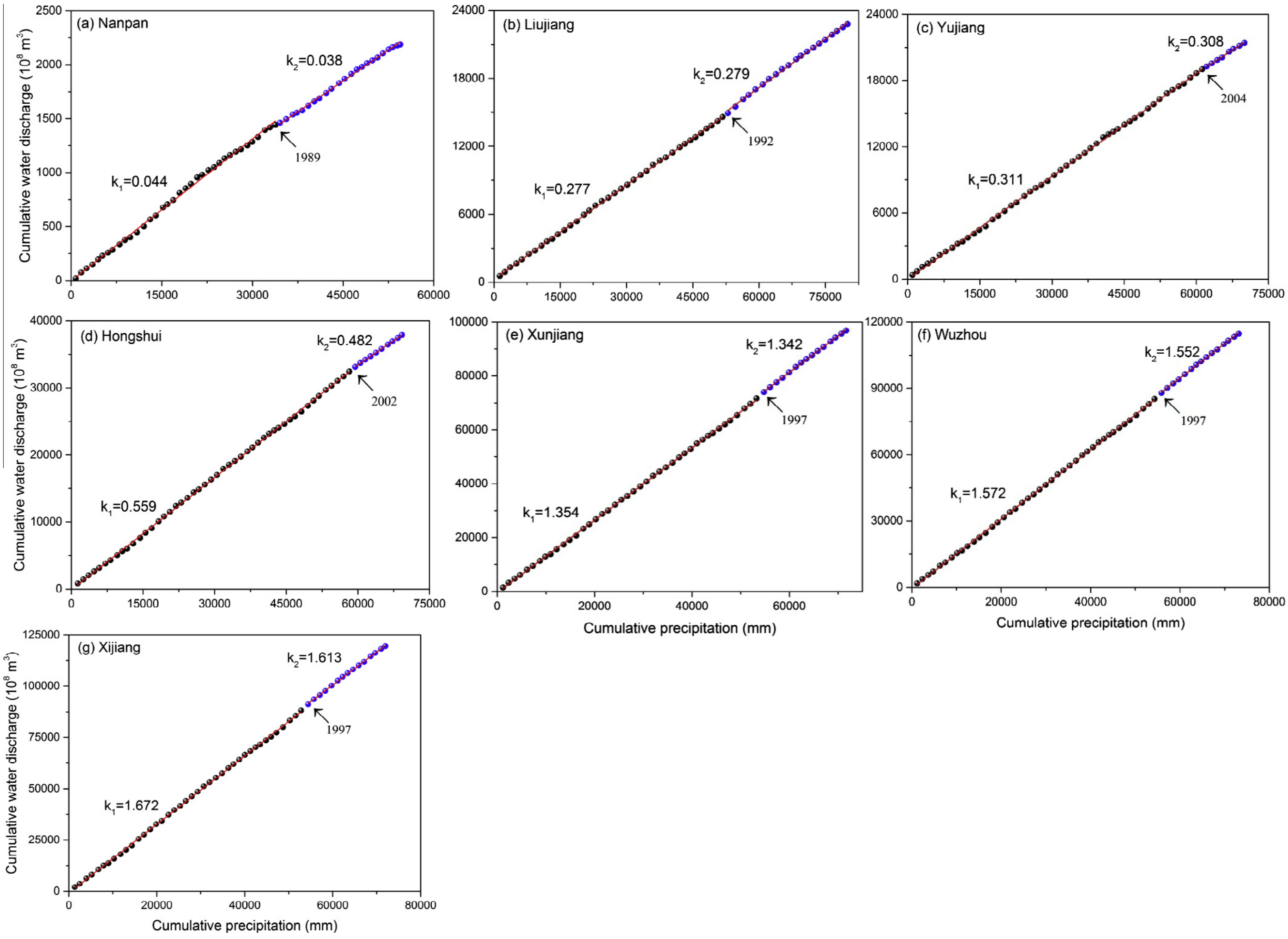

Fig. 4. Double mass curve analysis of annual water discharge and precipitation at different catchments. The straight lines are the regression lines for the cumulative data before and after the change point years.

(Naik and Jay, 2011), US Midwest (Xu et al., 2013a,b), Hutuo River basins (Wang et al., 2013), and Yangtze River basins (Zhao et al., 2015), precipitation (53–72%) contributing to water discharge reduction was larger than that of human activities. Water discharge, however, was mainly influenced by climate variability, while human activities had negligible influence on water discharge in our study region although a wide range of ecological environmental recovery measurements have been implemented. The subtropical humid karst areas in our study are characterized by shallow soils overlaying a highly irregular epikarst surface with a high infiltration rate (Zhang et al., 2014; Fu et al., 2015). This architecture is structurally different from the regoliths of non-karst, or even semi-arid and arid karst areas (Williams, 2008). Surface runoff would only occur when both soil and carbonate fissures and fractures were fully saturated with water (Wilcox et al., 2007; Hartmann et al., 2014). Most rainfall was transported to groundwater systems through carbonate fissures and fractures, whereas little was in the form of surface runoff (Peng and Wang, 2012; Fu et al., 2015). Due to the large storage capacity and high infiltration rate of karst carbonate fissures and fractures, the soil-epikarst system play important roles in runoff generation and may further weaken the effect of the human activities (e.g. land use change) on water discharge. Therefore, this particular soil-epikarst architecture is responsible for the difference in the effect of climate and human activities on water discharge between karst and non-karst areas.

Similarly, significant relationships were also detected between the annual precipitation and sediment discharge ($P < 0.05$). Interestingly, the coefficient of determination (R^2) between annual regional precipitation and water discharge are much greater than those between precipitation and sediment discharge (Table 7). This result implied that the influence of human activities on sediment discharge was considerably greater than that on water discharge for a given catchment in this karst region. Similar results was also found in non-karst areas, such as Nile and Colorado River (Vörösmarty et al., 2003), Mississippi River (Meade and Moody, 2010), Yellow River (Wang et al., 2015), and Yangtze River basins (Zhao et al., 2015). Human activities generally include land use change and dam construction in this region.

5.2. Effects of land use on sediment discharge

Due to the fact that water discharge is influenced by climate variability alone, only the impact of human activities (land cover change, NDVI dynamics, and dam construction) on sediment discharge was analyzed for the seven catchments in this study. Generally, land use is one of the most important factors influencing the frequency and the intensity of soil erosion, even exceeding the influence of rainfall intensity and slope gradient in some circumstances (Wei et al., 2007; Peng and Wang, 2012; Li et al., 2015). In this study, land cover (using "area" as an indicator) and NDVI change were used to reflect the variation in land use. Pearson

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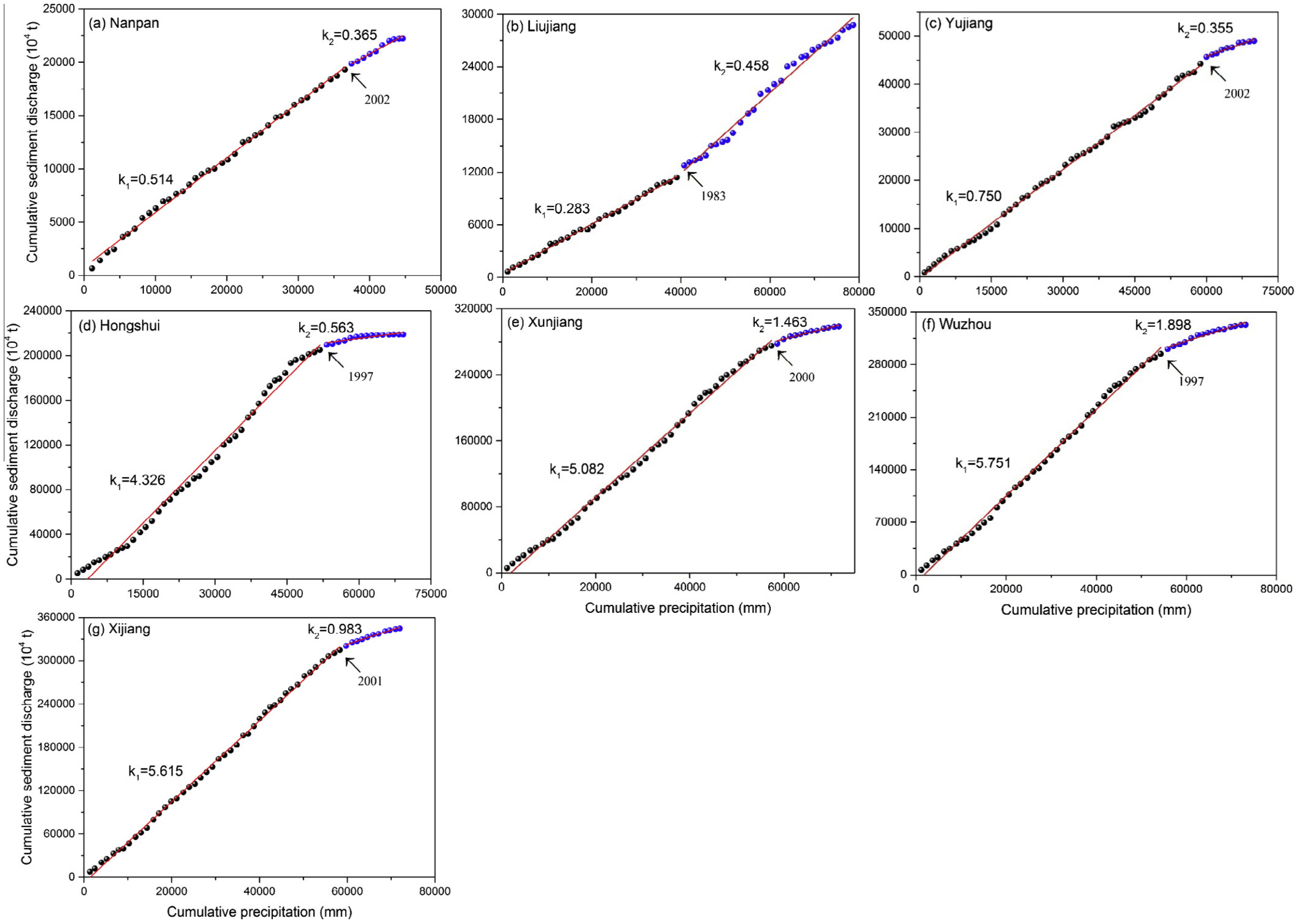

Fig. 5. Double mass curve analysis of annual sediment discharge and precipitation at different catchments. The straight lines are the regression lines for the cumulative data before and after the change point years.

Table 6
Attribution analysis of climate change and human activities impacts on sediment discharge.

Catchment	Period	S_o (10^4 t yr^{-1})	S_c (10^4 t yr^{-1})	ΔS (10^4 t yr^{-1})	ΔS_{clim} (10^4 t yr^{-1})	ΔS_{hum} (10^4 t yr^{-1})
Nanpan	Pre-2002	508				
	Post-2002	263	434	−245 (−48%)	−74 (−30%)	−171 (−70%)
Liujiang	Pre-1983	422				
	Post-1983	571	405	+149 (+35%)	−17 (−11%)	+166 (+111%)
Yujiang	Pre-2002	920				
	Post-2002	370	824	−550 (−60%)	−96 (−18%)	−454 (−82%)
Hongshui	Pre-1997	4768				
	Post-1997	656	4445	−4112 (−86%)	−323 (−8%)	−3789 (−92%)
Xunjiang	Pre-2000	6111				
	Post-2000	1887	5730	−4224 (−69%)	−380 (−9%)	−3843 (−91%)
Wuzhou	Pre-1997	7003				
	Post-1997	2317	6765	−4686 (−67%)	−316 (−5%)	−4448 (−95%)
Xijiang	Pre-2001	7150				
	Post-2001	2436	6653	−4714 (−66%)	−497 (−11%)	−4217 (−89%)

Note: S_o: observed mean annual sediment discharge; S_c: calculated mean annual sediment discharge; ΔS: changes in observed sediment discharge between pre-change and post-change year; ΔS_{clim} and ΔS_{hun} refers to the changes in observed mean annual sediment discharge impacted by climate change and human activities, respectively.

correlation analysis showed that no significant correlation was found between sediment discharge and land cover, suggesting that land cover change probably has no significant influence on sediment (Table 8). In fact, no remarkable land cover changes took place in all these seven catchments from 1990 to 2010. Although the built-up land area showed an increasing trend from 1990 to 2010 for all seven catchments, the ratio of this land cover area to the total area is no more than 2% and thus the effect of urbanization on sediment discharge may be negligible. Moreover, the influence of land cover change may be difficult to detect or identify in large catchments due to other human activities could probably reduce or mask the effect of land cover change on sediment discharge (Zhang et al., 2008a).

NDVI, as an indicator of the vegetation cover and health, can also be used to accurately reflect the land use change in relation to sediment discharge (Ma et al., 2010). No significant correlation

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Table 7
Regression equations between annual precipitation and water discharge, and annual precipitation and sediment discharge.

	Water discharge (10^8 m^3 yr^{-1})			Sediment discharge (10^4 t yr^{-1})		
	Equation	R^2	*P*-value	Equation	R^2	*P*-value
Nanpan	0.074*Pre*−30.85	0.602	<0.01	1.346*Pre*−789.25	0.621	<0.01
Liujiang	0.330*Pre*−62.138	0.452	<0.01	0.667*Pre*−404.74	0.092	0.013
Yujiang	0.507*Pre*−243.16	0.625	<0.01	2.279*Pre*−1906.73	0.464	<0.01
Hongshui	0.876*Pre*−392.23	0.678	<0.01	10.076*Pre*−2971.78	0.228	<0.01
Xunjiang	2.039*Pre*−864.09	0.691	<0.01	11.139*Pre*−8765.08	0.281	<0.01
Wuzhou	2.437*Pre*−1116.33	0.738	<0.01	11.577*Pre*−9015.43	0.263	<0.01
Xijiang	2.831*Pre*−1532.70	0.749	<0.01	13.490*Pre*−11391.41	0.384	<0.01

Note: *Pre* refers to annual precipitation.

Table 8
Pearson correlation coefficients between sediment discharge and land cover for seven catchments.

Catchment	Cropland	Woodland	Grassland	Water body	Built-up land	Unused land
Nanpan	-0.135^{ns}	0.769^{ns}	0.384^{ns}	-0.576^{ns}	-0.85^{ns}	0.444^{ns}
Liujiang	0.059^{ns}	-0.541^{ns}	0.157^{ns}	-0.115^{ns}	-0.129^{ns}	0.187^{ns}
Yujiang	-0.511^{ns}	0.515^{ns}	0.545^{ns}	-0.454^{ns}	-0.702^{ns}	0.869^{ns}
Hongshui	-0.402^{ns}	0.707^{ns}	0.445^{ns}	-0.621^{ns}	$-0.625^{ ns}$	-0.021^{ns}
Xunjiang	-0.438^{ns}	-0.173^{ns}	0.619^{ns}	-0.526^{ns}	-0.786^{ns}	0.260^{ns}
Wuzhou	-0.456^{ns}	-0.161^{ns}	0.627^{ns}	-0.520^{ns}	-0.770^{ns}	0.285^{ns}
Xijiang	-0.619^{ns}	-0.081^{ns}	0.792^{ns}	-0.580^{ns}	-0.829^{ns}	0.474^{ns}

Note: ^{ns} Correlation is non-significant at the 0.05 level.

was found between NDVI and sediment discharge in Nanpan, Yujiang, and Hongshui catchments ($P > 0.05$, Fig. 6a, c, d), while the sediment discharge significantly decreased with NDVI in the other four catchments ($P < 0.05$, Fig. 6b, e–g). For all seven catchments, it was obvious that sediment discharge was closely related to NDVI ($P < 0.05$, Fig. 6h). Overall, the land use change can influence the sediment discharge although this influence is not significant for some catchments.

In non-karst areas, such as Yellow River basin, the increase in perennial vegetation coverage was the dominant factors responsible for the sediment discharge reduction (Wang et al., 2015). The sediment concentration negatively correlated with vegetation coverage with a R^2 of 0.74 in this region (Liu et al., 2014a,b; Wang et al., 2015). This implied that the effect of land use change on sediment discharge in the Yellow River basin is considerably greater than those in our study area. Indeed, although vegetation cover

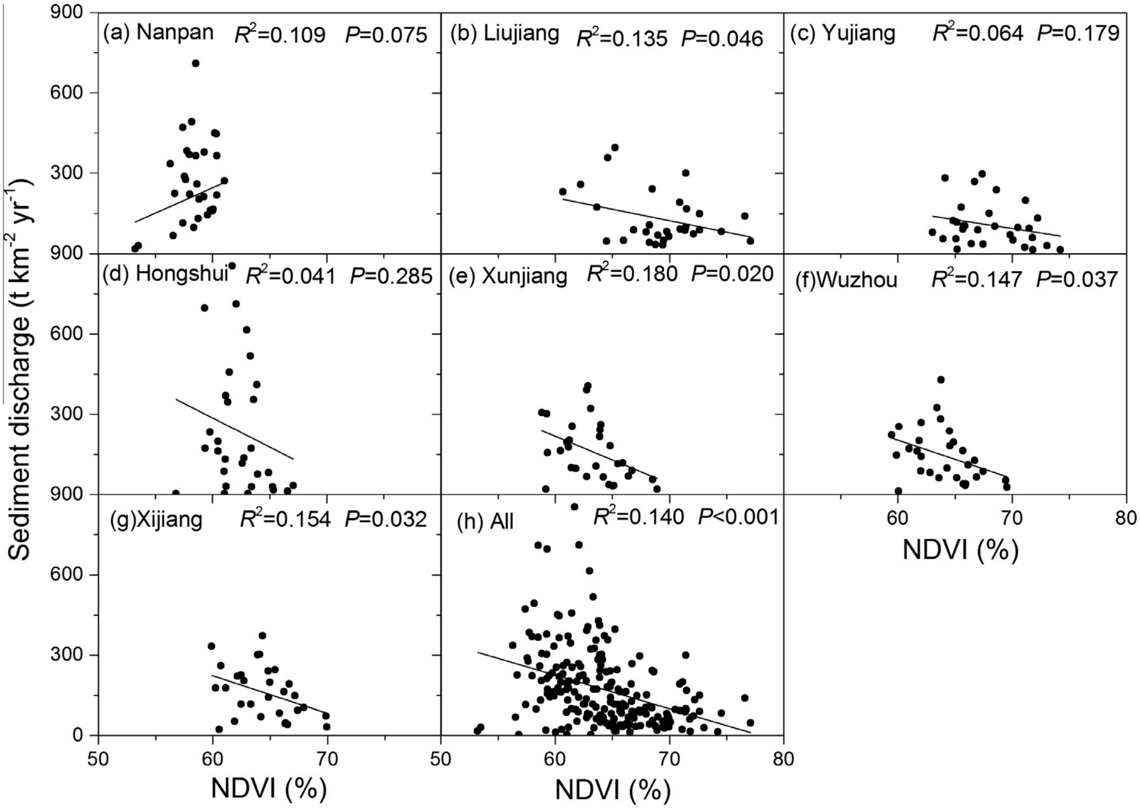

Fig. 6. Sediment discharge as a function of NDVI.

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can stabilize soils and minimize soil erosion, it is not the only factor in reducing the rate of soil erosion and sediment delivery. Another important factor is epikarst development in karst areas (Williams, 2008; Peng and Wang, 2012). There is a general consensus that subsurface flow is the main runoff generation mechanism in karst areas (Fu et al., 2015). The soil was mainly lost through subsurface flow beneath the soil surface, while only a small fraction of the surface soil was washed away through overland flow. Sinkholes, which can connect with the subterranean rivers, are widely distributed in a karst catchment (Li et al., 2010). During a rainfall event, especially during extreme storms, sediment-laden flows can drain out through the sinkholes (Bai et al., 2013). Thus, a large amount of sediments were lost from the sinkhole to underground drainage systems, and the effective of vegetation cover in reducing soil erosion is greatly limited in karst areas.

5.3. Effects of dam construction on sediment discharge

The dams can trap sediments and have been one of the most effective measures to control sediment discharge (Dai et al., 2008; Zhang et al., 2008a). Numerous dams have been constructed within the Xijiang River basin since the Chinese government issued a Soil Preservation Law in 1991 (Zhang and Lu, 2009; Wu et al., 2012). In Nanpan catchment, the CSD dam (see Table 2 for definitions of dam abbreviations) was closed in 2001 and the change point year in sediment discharge then occurred in 2002 (Tables 2 and 5). The sediment discharge in pre-dam period is significantly greater than those in post-dam period (Fig. 7a). This implied that the CSD dam play a decisive role in reducing sediment discharge at Nanpan catchment. In Liujiang catchment, no significant difference was detected in sediment discharge between pre-dam and post-dam period although the MD dam was operated in 1971 (Fig. 7b; Table 2). Indeed, the sediment discharge showed a small increasing trend in this catchment. As mentioned above, one explanation is that there is only one large MD dam with a storage capacity of 0.3 km^3 located in this catchment, and no other large dams were constructed to reduce sediment discharge (Zhang et al., 2008a; Wu et al., 2012). One alternative possibility is that this catchment experienced serious rock desertification due to severe soil and water loss (Zhang et al., 2008a). In turn, the exacerbated rock desertification also enhanced soil erosion (Peng and Wang, 2012; Feng et al., 2014). Such a vicious circle has a detrimental effect on the ecosystem and attention should be paid to address this issue in Liujiang catchment (Dai et al., 2008; Zhang et al., 2008a). In Yujiang catchment, no significant sediment discharge reduction was detected after the CD dam was constructed in 1966, while the sediment discharge decreased by 66% from $6.32 \times 10^6\ t\ yr^{-1}$ in 1966–2005 to $3.18 \times 10^6\ t\ yr^{-1}$ in 2006–2011 after the BD dam closed (Fig. 7c). The storage capacity of BD dam is 5 times greater than that of the CD dam and thus is more effective in reducing the sediment discharge. In Hongshui, Xunjiang, Wuzhou, and Xijiang catchments, a series of dams such as XD, CD, ED, and DD dams were constructed during 1950s–1991, but the sediment discharge presented an increasing trend (Fig. 7d–g). This phenomenon was probably caused by the deforestation. In this period, the rapid economic development in agriculture enhanced the massive deforestation (Dai et al., 2008; Wu et al., 2012). The influence of deforestation outweighed the effect of dam construction on sediment discharge before 1991, resulting in a significant human-induced increase in sediment discharge. After 1991, some large dams such as YD, TD, BD, and LD were commissioned, and the sediment discharge showed a decreasing trend since (Fig. 7d–g). As a result of sediment deposition in the YD dam, the sediment discharge at Hongshui catchment rapidly decreased by 59% from $6.57 \times 10^7\ t\ yr^{-1}$ in 1982–1991 to $2.71 \times 10^7\ t\ yr^{-1}$ in 1992–1997 (Fig. 7d). Following the TD dam construction, sediment discharge in 1998–2005 decreased by 44–62% as compared to those in 1992–1997 for these four catchments (Fig. 7d–g). Sediment discharge drastically decreased by 45–86% after construction of the BD and LD dam (Fig. 7d–g) for Hongshui, Xunjiang, Wuzhou, and Xijiang catchments. Therefore, the dams (in particular the large reservoirs) quite effectively reduce the sediment discharge (Wu et al., 2012).

The total annual deposition in all dams in the Xijiang River was estimated to be 3.90×10^8–$6.07 \times 10^8\ t\ yr^{-1}$, which is one order of magnitude greater than the annual sediment discharge from the Xijiang River into the sea (Dai et al., 2008). Since dams can efficiently trap sediments coupled with no significant trend was detected in the water discharge, the water flowing out of the dam generally had a lower sediment concentration than before. It is widely known that soil detachment occurs when the sediment discharge is less than sediment transport capacity (Zhang et al., 2009). The low sediment concentration in rivers could have enough energy to detach soil particles and sediments from the bulk material since the energy required for sediment transport is smaller than that for detachment (Li et al., 2015). Thus, impoundment usually tends to cause severe erosion along the river bed and bank downstream from the dam (Dai et al., 2008). Reinforced embankment is hence essential to control soil erosion along the lower reaches below the dam.

In karst or non-karst areas, dams can both greatly reduce the sediment discharge in rivers, but the magnitude of this reduction is different among various rivers. In some rivers with high sediment discharge, effectiveness of dams decreases with time as they are progressively filled up with deposited sediment (Wang et al., 2015). For example, in the Yellow river basin, the number of check-dams decreased since the 1980s as the storage capacity of dams are gradually reduced or became non-existent because of the frequently occurring floods, thereby having relatively less impact on sediment discharge over time (Wang et al., 2011b, 2015; Liang et al., 2015). Dams, however, still play a dominant role in sediment retention in our study region, at least in the short term, due to its lower sediment discharge compared to those in Yellow River. Because of the vegetation restoration exerted limited effect on sediment discharge reduction in our study region, it is of great importance to maintain a sustainable sediment trapping dam systems. Thus, it should be paid particular attention to regularly dredge the area upstream of dams and further to replace the slowly filling sediment trapping dams in future.

5.4. Implications

Compared to non-karst areas (e.g. Loess Plateau), the karst landscape generated relatively lower sediment yield (Miao et al., 2010, 2011; Gao et al., 2013). Soil erosion in karst region of southwest China, however, is still serious due to its lower soil loss tolerance (Feng et al., 2014). In pure and thick pure limestone areas, the content of the insoluble residues in pure carbonate rocks is quite small (<5%) and hence it required 2000–8000 years to form the 1 cm soil (Fu et al., 2015). The soil also has a shallow depth with 20–40 cm on mountaintops and 50–150 cm on mountainsides. Because of the slow formation rate and shallow depth of the soil, the soil loss tolerance is only 30–68 $t\ km^{-2}\ yr^{-1}$ (Peng and Wang, 2012; Feng et al., 2014). For seven catchments, the mean annual sediment yield (115–301 $t\ km^{-2}\ yr^{-1}$) is all higher than the soil loss tolerance. Thus, the soil erosion risk is quite high and should be paid great attention in the karst area of southwest China, especially in catchments with serious rock desertification.

Our result demonstrated that the water discharge changes were mainly controlled by variations in precipitation, while changes in sediment discharge were primarily caused by human activities. Similarly, previous studies also showed that the

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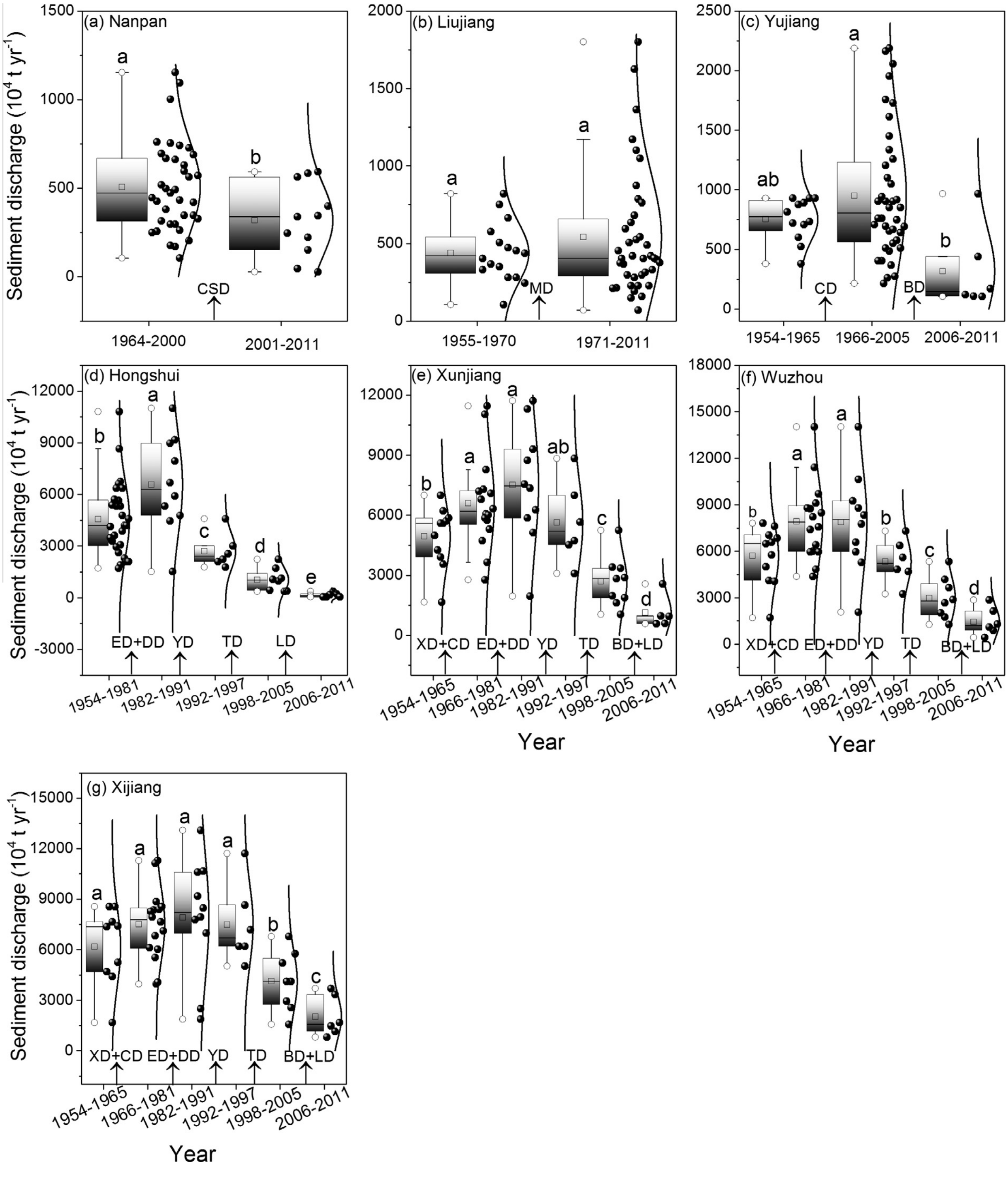

Fig. 7. Comparison of the sediment discharge between pre-dam and post-dam period for each catchment. The curved line to the right of each box is the distribution curve. Different letters indicate significant differences at $P < 0.05$. The definitions of dam abbreviations can be referred to Table 2.

detected trends in water discharge were mainly attributed to climate change in eastern or Pacific Northwest of the United States (Small et al., 2006; Luce and Holden, 2009). On the contrary, human activities have been a main cause of drastic declines in water discharge in some other regions, such as Yellow River basin (Miao et al., 2011; Wang et al., 2011a; Gao et al., 2013). For sediment discharge, human activities contributed 65% and 86% in Yangtze River and Yellow River basin, respectively (Wang et al., 2015; Zhao et al., 2015), while 99% of sediment decrease in Nile and Colorado rivers can be ascribed to dam construction (Vörösmarty et al., 2003). Actually, water and sediment discharge depends on many interacting factors, and a factor that is important in one river can be insignificant in another (Wu et al., 2012). That is, the causes of changes in water and sediment discharge may differ from river to river. Therefore, knowledge of the driving factors for these changes between different rivers is needed. Fortunately, in our study, we found that sediment discharge reductions increased with the relatively regulated area for these seven catchments (Fig. 3). An increase in the relatively regulated area would have greater potential for effectively reducing sediment delivery for a given catchment. This finding contributes valuable insight for evaluation and implementation of long-term sustainable regional planning and development of effective conservation strategies.

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6. Conclusions

Karst regions represent 7–12% of the Earth's land surface and provide drinking water for almost 25% of the world's population. Due to the special geologic condition, karst region is characterized by thin surface soil, high infiltration capacity, and complex topography, and thus generally is quite distinct from non-karst areas. The effects of climate and human activities on water and sediment discharge may be also different between karst and non-karst regions. Numerous studies focused solely on non-karst regions, however, the impacts of climate and human activities on water and sediment discharge have rarely been assessed for karst regions. For this study, seven karst catchments located in southwest China were chosen to firstly investigate the trends and abrupt changes in water and sediment discharge since the 1950s. The relative contributions of climate variability and human activities to water and sediment discharge were then evaluated using double mass curves, and potential factors influencing the water and sediment discharge changes were also quantified. The results showed that annual rate of decrease in water discharge ranged from -0.21×10^8 to -3.68×10^8 m^3 yr^{-1}, which was mainly controlled by the climate variability. Sediment discharge, however, showed a significantly decreasing trend at a rate of -7×10^4 to -101×10^4 t yr^{-1} for six of the seven catchments except Liujiang. Specifically, we found that the magnitude of reduction in sediment discharge (%) significantly increases with the extent of flow regulation as measured by the ratio of the area upstream the dam to the total catchment area ($R^2 = 0.98$, $P < 0.01$). A significant increase in sediment discharge in Liujiang catchment is thus probably due to its minimum extent of flow regulation. No obvious abrupt changes were observed in water discharge, but an abrupt change occurred around 2000 in sediment discharge for six of the seven catchments. The changes in sediment discharge were predominantly impacted by human activities, which were directly responsible for 70–111% of the variations in sediment discharge. The sediment discharge decreased as NDVI increases for four catchments ($P < 0.05$). Unlike non-karst areas, the special soil-epikarst architecture in karst areas can reduce the effective of vegetation cover in reducing soil loss. Due to the comparatively low sediment discharge in karst areas, dams can still play a dominant role in sediment retention. Reduction in sediment discharge was influenced by land use change, but the dam construction plays a predominant role in karst regions. Although, generally speaking, the rate of soil loss is not as high as in other non-karst regions, the risk of soil erosion needs to be carefully managed because of the shallow depth and slow formation rate of the soil in karst areas. The findings in this study would provide scientific basis for optimum water and catchment management for karst regions.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhydrol.2016.09.049.

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