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Assessing Impacts of Climate Change and Human Activities on Streamflow and Sediment Discharge in the Ganjiang River Basin (1964–2013)

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Abstract: National large-scale soil and water conservation controls on the Gangjiang River basin have been documented, but the effect of governance on regional watershed hydrology and how the main driving factors act have not been systematically studied yet. To do this, this study evaluated changing trends and detected transition years for both streamflow and sediment discharge using long-term historical records at seven hydrological stations in the Ganjiang River basin over the past 50 years. The double mass curve (DMC) method was used to quantify the effects of both climate change and human activities on hydrological regime shifts. The results showed that the distributions of precipitation, streamflow, and sediment discharge within a year are extremely uneven and mainly concentrated in the flood season of Jiangxi Province. None of the stations showed significant trends over time for either annual precipitation or streamflow, while the annual sediment discharge at most stations decreased significantly over time. The estimation of sediment discharge via DMC indicated that after the transition years, there were rapid reductions in sediment discharge at all hydrological stations, and the average decline degree of midstream and downstream were much larger than that of upstream. Human activities, especially the increase of vegetation cover and construction of large and medium-sized reservoirs, provided a significantly greater contribution to the reduction of sediment discharge than did precipitation changes. As a case study of river evolution under global change environment, this study could provide scientific basis for the control of soil erosion and the management of water resources in Ganjiang River, as well as for the related research of Poyang Lake and the Yangtze River basin of China.

Keywords: eco-hydrology; human activity; precipitation; transition year; Ganjiang River basin

1. Introduction

Climate change could influence regional hydrological cycles by altering precipitation, evapotranspiration, soil moisture, and temperature, and then causing changes in river runoff [1,2]. Spatiotemporal changes to precipitation amount and intensity resulting from climate change may lead to increased occurrence of erosive rainfall events and increased sediment yield in watersheds [3]. In addition, a large number of studies have shown that human activities, such as large-scale vegetation destruction and reconstruction and massive construction of water conservancy facilities (e.g., reservoirs) may lead to major changes in land use patterns, which can greatly change the underlying surface conditions of the basin, thereby producing changes in runoff and sediment processes in a river basin [4–7]. Research shows more than half of the world's large river systems have been impacted by humans to varying degrees. The Chinese Pearl, Yellow and Yangtze River, Yalu Jiang, Liao He, Hai He, and Qiantang Jiang river systems and others have been strongly affected [8–12]. As global climate warming increases due to human activities, there is increasing concern in the scientific fields of water conservancy engineering, river geomorphology, and land water cycle regarding trends in water movement and sediment deposition, and regarding the contribution that climate change and human activities make to these processes [13–16].

Relevant studies in China and abroad are mainly concentrated in large rivers and their tributaries. For example, an analysis of driving forces affecting long-term changes in sediment yield has been made for large Russian rivers discharging to the Arctic Ocean [13]. The results of that study showed that changes in sediment yield depended more on human activities than on climate change, and the local increases or decreases in sediment yield were the result of gold mining activities and construction of reservoirs in the upper reaches of the Ob and Yenisei rivers, respectively. The construction of large reservoirs and the resultant flow diversion have resulted in almost complete sediment trapping on several large river basins such as the Colorado and Nile [8]. Other heavily regulated drainage basins with large reservoirs resulting in large sediment retention rates are found in Europe, North America, Africa, and Australia/Oceania [8]. A research study identifying driving factors for changes in streamflow of the Xinjiang River basin in Poyang Lake showed that climate (especially precipitation) played a dominant role in changing basin hydrology and streamflow, while the seasonal variations of basin hydrology and water balance were strong functions of land-use change and vegetation distribution in the basin [17]. That study also found that different land-cover patterns can cause increases or decreases in streamflow in different seasons. Relevant studies on the major Chinese river systems have concluded that human activities have contributed more to changes in annual river and sediment discharge than climate variability, (e.g., 87% in the Wuding River, 83% in the Yellow River, and 71% in the Yangtze River basin), and the impacts of human activities on the whole basin have increased with time [7,12,18–20].

The Ganjiang River is the most important major river in the Poyang Lake River basin and is also one of the eight major tributaries of the Yangtze River. Variation in runoff and sediment in the Ganjiang River not only affects the water volume and siltation of Poyang Lake, but also affects the variation of runoff and sediment in the lower reaches of the Yangtze River [18,21]. Historically, the Ganjiang River Basin also has the most intense area of soil erosion in Poyang Lake. Since the 1980s, a series of soil erosion control projects have been implemented in this area. These projects include the pilot project of comprehensive control of the Tangbei River small watershed, eight key projects of soil and water conservation in China, key construction projects of national soil and water conservation, long-term control project of national agricultural comprehensive development, and key projects of soil and water conservation in the Poyang Lake Basin [22]. In recent years, relevant research results have been achieved in the study of streamflow and sediment changes in the Ganjiang River. Previous research has demonstrated that, driven by multiple factors, annual runoff in this region has not changed significantly in recent decades, while annual sediment transport has shown a significant downward trend [21,23,24]. Previous studies have identified and quantified the trends of streamflow and sediment discharge in the Ganjiang River basin but have mainly focused on the inter-annual variation tendency at one to three hydrological stations. It remains unclear as to whether changes occur at seasonal or monthly scales, and whether transition years exist in the long time series of hydro-climatic data, and to what extent the driving forces (e.g., climate change and human activities) are responsible for these changes. Therefore, the purposes of this study were to: (a) Identify the seasonal distribution of hydro-meteorological variables; (b) identify trends and abrupt changes in precipitation, streamflow, and sediment discharge in the upper, middle, and lower reaches of the Ganjiang River basin; and (c) estimate the contribution rate of both climate change and human activities to changes in runoff and sediment transport during the past 50 years.

2. Materials and Methods

2.1. Study Area and Datasets

2.1.1. Study Area

This study was undertaken in the Ganjiang River basin (113.58°–116.63° E, 24.52°–28.75° N), which is located in Jiangxi Province of south China (Figure 1). The source of the Ganjiang River lies in the jungle valley below Ganyuandong Stream of Wuyi Mountain, which borders both Jiangxi and Fujian Provinces. It flows from south to north through more than 20 counties and cities such as Ganzhou, Wan'an, Ji'an, and Zhangshu to Nanchang City and discharges into Poyang Lake in four branches [24]. The catchment area above the Ganjiang control station Waizhou is 80,948 km^2, and the main stream of the Ganjiang River is 766 km, where its upstream (Gongshui River basian), midstream, and downstream lengths occupy 255 km, 303 km, and 208 km, respectively [21]. The Ganjiang River is located in a subtropical humid monsoon climate region with mild climate, abundant rainfall, four distinct seasons, and sufficient solar radiation. The annual average temperature, precipitation, and evaporation are 17.6 °C, 1543 mm, and 816 mm, respectively. The water resources of this area are plentiful. Precipitation is mostly concentrated in April–June, which is also the main flood season for the Ganjiang River, during which time precipitation accounts for 46.8% of the annual precipitation. The average annual runoff is 680.3×10^3 m^3, which is mainly a result of precipitation, and the regional distribution and inter-annual variation of annual runoff is similar to that of precipitation.

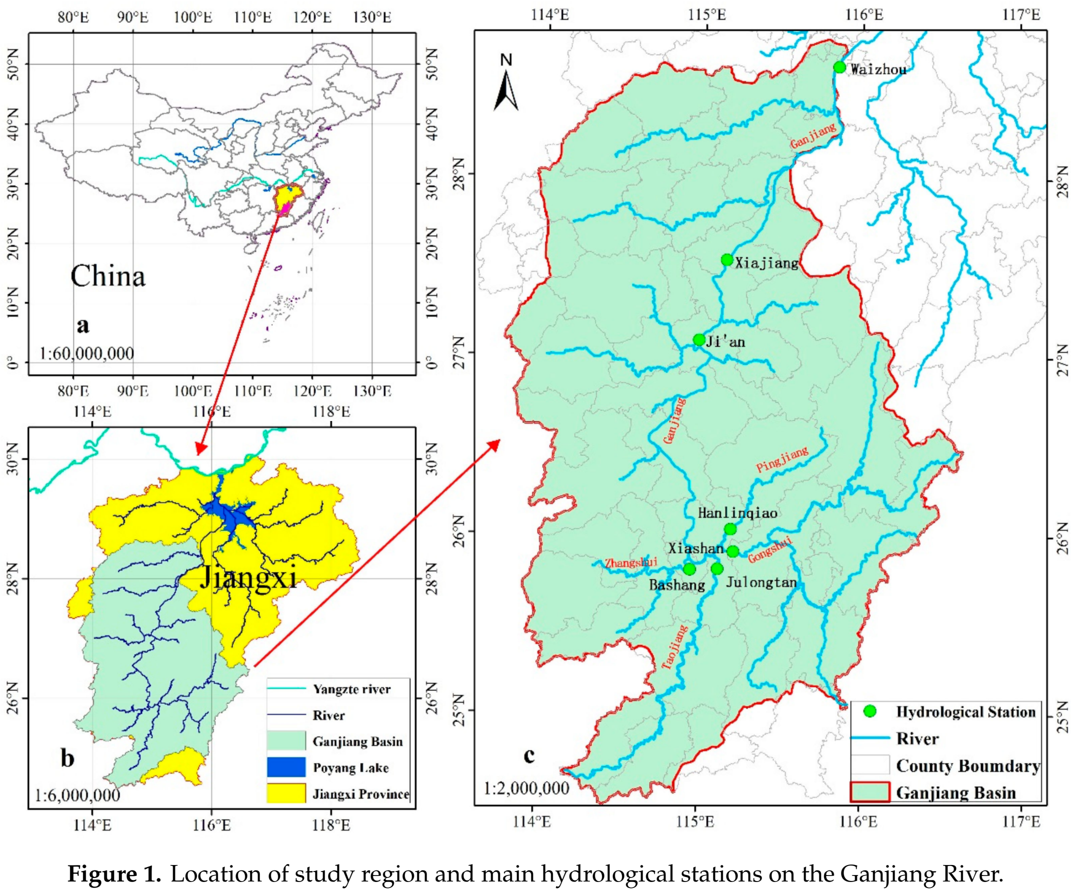


Figure 1. Location of study region and main hydrological stations on the Ganjiang River.

2.1.2. Data

The long-term daily flow and sediment content datasets from the Ganjiang River basin were provided by the Hydrology Bureau of Jiangxi Province, while Xiajiang station only had yearly data of streamflow and sediment discharge. Daily precipitation data were obtained from the National Meteorological Information Centre of the Chinese Meteorological Administration, and the water resources census data of large and medium-sized reservoirs were from the Jiangxi Provincial Institute of Water Sciences. Four representative hydrological stations in the upstream portion of this region were selected, namely the Bashang, Xiashan, Hanlinqiao, and Julongtan hydrological stations, which are the control stations of Zhangshui, Gongshui, Pingjiang, and Taojiang, respectively. Additionally, the Ji'an hydrological station in the middle reaches and the Ganjiang control station Waizhou in the lower reaches were also selected. The time spans of all hydrological stations were 1964–2013. More detailed information for these seven stations are given in Table 1.

Table 1. Hydrological stations on the Gangjiang River Basin.

Location	Hydrological Stations	Drainage Area (km^2)	Latitude	Longitude	Precipitation † (mm)	Streamflow † (10^8 m^3)	Sediment Discharge † (10^4 t)
Upstream	Bashang	7657	114°57′	25°49′	1383	62.50	95.63
	Xiashan	15,975	115°10′	25°55′	1510	136.22	187.90
	Julongtan	7751	115°07′	25°49′	1547	60.95	121.76
	Hanlinqiao	2689	115°12′	26°03′	1567	23.33	83.59
Midstream	Ji'an	56,223	114°59′	27°06′	1522	469.27	643.51
	Xiajiang	62,724	115°15′	27°55′	1508	515.14	695.57
Downstream	Waizhou	80,948	115°84′	28°63′	1596	683.59	836.04

† Average annual value over the shown time span.

2.2. Methodologies

In this study, the Mann-Kendall test [25,26], Pettitt analysis [27], and DMC method along with its corresponding regression equations [5,28] were used to detect the seasonal and annual trends, transition years of hydro-meteorological variables (e.g., precipitation, streamflow, and sediment discharge), and the driving forces influencing their variations in the Ganjiang River basin.

2.2.1. Trends Test to Detect Changes of Precipitation, Streamflow, and Sediment Discharge

The non-parametric Mann–Kendall statistical test has been widely used for trend detection in the time series of hydro-climatic data [29]. For a group of hydrological time series variables, X_i (i = 1, 2, 3, ..., n), the Mann–Kendall test statistic S is calculated by:

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

where $\operatorname{sgn}(x_j - x_i) = \begin{cases} 1 & x_j - x_i > 0 \\ 0 & x_j - x_i = 0 \\ -1 & x_j - x_i < 0 \end{cases}$. n is the sequence length. When $n \geq 10$, the statistic S obeys the normal distribution, and the equation of its mean $E(S)$ and variance $D(S)$ are $E(S) = 0$, $D(S) = \frac{n(n-1)(2n+5)}{18}$, respectively. Furthermore, the Z statistics obtained from the Mann–Kendall test can be used to judge whether or not the observed variable is statistically significant. The formula for Z is given as:

$$Z = \begin{cases} \frac{S-1}{\sigma} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sigma} & S < 0 \end{cases} \tag{2}$$

where $\sigma = \sqrt{D(S)}$. $Z_{(1-\alpha/2)}$ is the critical value of the standard normal distribution with a probability exceeding $\alpha/2$. Absolute values of Z greater than or equal to 1.28 and 1.64 show that the Mann–Kendall trend test has been found to be significant at the confidence levels 90% and 95%, respectively.

2.2.2. Breakpoint Analysis to Detect the Transition Year

The non-parametric Pettitt test with a statistical significance level of 95% was used to detect the transition year in which an abrupt change in the hydrological variables and precipitation data may have occurred. Here, the test uses the Mann–Whitney statistic, $U_{t,T}$ to test whether two sample sets $X_1, X_2, \ldots \ldots X_t$ and $X_{t+1}, \ldots \ldots X_T$ are from the same population [27]. For successive sequences, the statistic, $U_{t,T}$, is expressed as:

$$U_{t,T} = U_{t-1,T} + \sum_{j=1}^{T} \operatorname{sgn}(x_t - x_j) \text{ for } t = 2, \ldots\ldots, T \tag{3}$$

and

$$\operatorname{sgn}(x_t - x_j) = \begin{cases} 1 & x_t - x_j > 0 \\ 0 & x_t - x_j = 0 \\ -1 & x_t - x_j < 0 \end{cases}. \tag{4}$$

Here, the statistic is used to count the number of times that a member of the first sample exceeds a member of second sample. In this study, the test statistic K_T and corresponding probability (p), with their calculation formulas are given as:

$$K_T = \max\left|U_{t,T}\right| \tag{5}$$

$$p = 1 - \exp\left(\frac{-6{K_T}^2}{T^3 + T^2}\right). \tag{6}$$

When the absolute value of K_T is greater than the corresponding value in the horizontal line of 95%, the alternative hypothesis of the Pettitt method is found, and the most significant change-point is identified by the corresponding year of the maximum K_T. Conversely, the null hypothesis of the Pettitt method means the absence of a change point.

2.2.3. Double Mass Curve to Detect the Impact of Precipitation and Human Activity

In this study, DMC along with the linear regression lines were used to quantify the variation of streamflow and sediment discharge before and after the transition years, and further used to analyze the contribution rate of the driving forces of this variation [30]. The relative changes of total sediment discharge for the period after the transition years could be estimated by the equations fitted to the double curves before the transition years, which can be expressed as:

$$S_c = a * \sum P + b \tag{7}$$

where S_c is the calculated cumulative sediment discharge, $\sum P$ is the observed cumulative precipitation, and a and b are parameters estimated by the linear regression lines in the double mass curve before the transition year.

Furthermore, the contribution rate of climate change (especially rainfall) and human intervention could be estimated by the following equations:

$$\triangle S' = \overline{S_{obs1}} - \overline{S_{obs2}} \tag{8}$$

$$C_r = \frac{\overline{S_{obs1}} - \overline{S_{cal2}}}{\triangle S'} \times 100 \tag{9}$$

$$C_h = 1 - C_r \tag{10}$$

where $\triangle S\prime$ is the reduction in average observed sediment discharge between the period before and after the transition years in the Ganjiang River basin. $\overline{S_{obs1}}$ and $\overline{S_{obs2}}$ are the average observed sediment discharge for the periods before and after the transition years, respectively. $\overline{S_{cal2}}$ is the average calculated sediment discharge after the transition year. C_r and C_h are the contribution rate of rainfall and human activity, respectively.

3. Results and Discussion

3.1. Seasonal Distribution of Hydro-Meteorological Variables

The distribution of monthly hydro-meteorological variables at six stations is given in Table 2. The average annual rainfall (about 1500 mm) in this area is very abundant, and due to the difference of drainage area, the range of annual streamflow is spaning from 23.56×10^8 m^3 of Hanlinqiao to 685.62×10^8 m^3 of Waizhou station, and the sediment transport in this area is less than 10^7 t. The annual distribution of precipitation, streamflow, and sediment are extremely uneven, and mainly concentrated in the flood season (April to September) of Jiangxi Province. The cumulative values in the first half of the flood season (April–June) accounted for about 70% of that in total flood season. Specifically, precipitation in the flood season accounted for greater than 65% of the total annual precipitation, and the proportion of streamflow was a little greater than that of precipitation. The sediment discharge in this period accounted for nearly 85% of the annual sediment discharge.

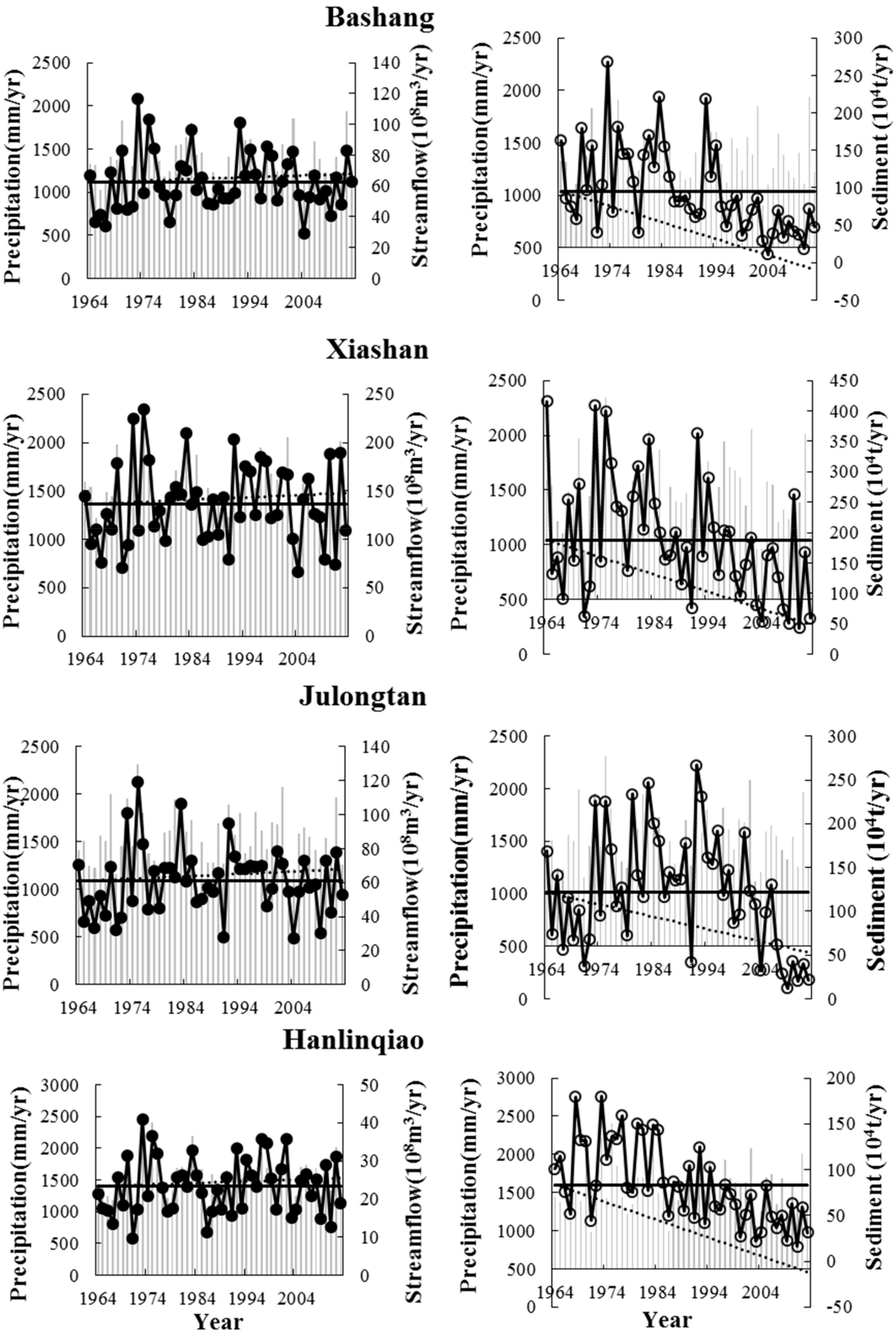
3.2. Trends in Seasonal and Annual Hydro-Meteorological Variables

The results of the Mann–Kendall trend test of annual and seasonal hydro-meteorological variables are summarized in Table 3. Less than one-half (43 of 105) of the trend tests showed significant changes. Only 11 of the 43 significant Z statistic values indicated upward trends (six for streamflow and five for precipitation), while 32 of the 43 values indicated significant downward trends. Among the 43 significant trends, 26 were significant at the 95% confidence level and the other 17 were significant at the 90% confidence level. Variations in annual precipitation, streamflow, and sediment discharge over time are shown in Figure 2. No significant trend ($p > 0.05$) was found in the variations of either precipitation or streamflow (Table 3). Precipitation was seen to fluctuate around the mean value (1500 mm), trend lines showed streamflow increasing over time at all stations, and some changes in the magnitude of these variables were relatively large, but their differences were not significant at $p = 0.01$ ($|Z| < 1.28$). Annual sediment discharge declined over time, and downward trends were significant at $p = 0.05$ ($|Z| \geq 1.64$) for all stations in the upstream, midstream, and downstream of Ganjiang River basin.

In the analysis of precipitation, streamflow, and sediment discharge by season, 37 of the 72 records showed significant changes. Among these were 10 precipitation records (two at $p = 0.05$), eight streamflow records (four at $p = 0.05$), and 19 sediment discharge records (14 at $p = 0.05$). For the seasonal periods of January–March, April–June, July–September, and October–December, there were 10, 9, 10, and 8 records with significant trends, respectively (Table 3). For the flood period (from April to September), precipitation and streamflow showed significant downward trends in main raining seasons (April–June), which was completely opposite to that in July–September at several hydrological stations like Bashang and Hanlinqiao. For the non-flood period, except Hanlinqiao station, the streamflow in other stations had no significant trend change, while the precipitation showed significant downward trends in October–December, and both upward and downward trends in January–March season. The sediment discharge of most stations showed significant downward trends in all seasons throughout the year.

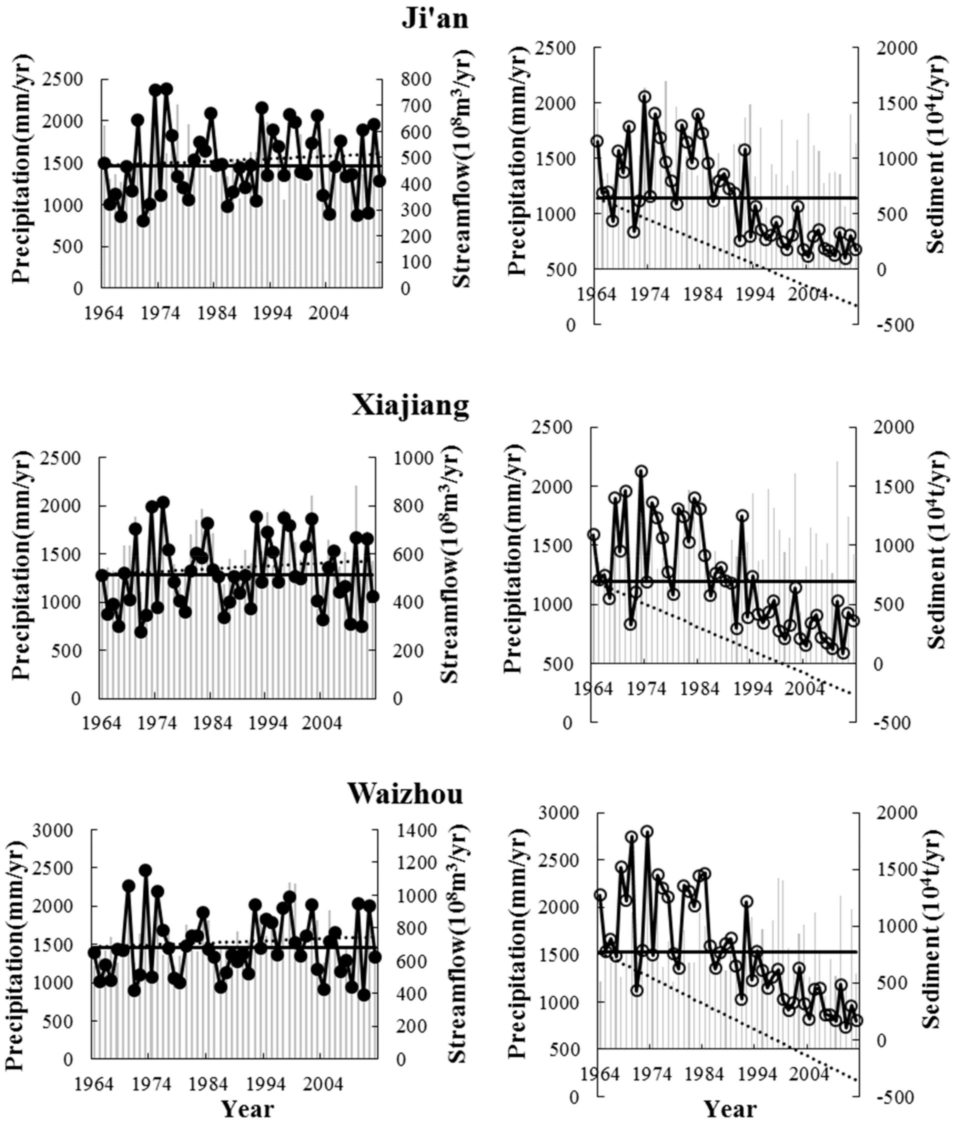
Table 2. Monthly mean precipitation (P), streamflow (R), and sediment discharge (S) in the Gangjiang River basin and percentage of annual amount.

Stations	Item	January	February	March	April	May	June	July	August	September	October	November	December	Year	April–September
Waizhou	*P* (mm)	67.12	100.10	163.74	227.40	245.44	300.95	144.35	113.51	66.70	55.40	66.56	44.38	1595.67	1098.36
	Percentage	4.21%	6.27%	10.26%	14.25%	15.38%	18.86%	9.05%	7.11%	4.18%	3.47%	4.17%	2.78%	100.00%	68.83%
	R (10^8 m^3)	23.15	30.06	58.93	96.08	110.10	124.07	73.58	48.57	41.35	30.71	26.54	22.46	685.62	493.76
	Percentage	3.38%	4.39%	8.60%	14.01%	16.06%	18.10%	10.73%	7.08%	6.03%	4.48%	3.87%	3.28%	100.00%	72.02%
	S (10^4 t)	9.17	17.70	72.01	157.78	173.40	213.40	82.11	38.54	35.92	18.49	10.67	6.84	836.04	701.15
	Percentage	1.10%	2.12%	8.61%	18.87%	20.74%	25.53%	9.82%	4.61%	4.30%	2.21%	1.28%	0.82%	100.00%	83.87%
Ji'an	*P* (mm)	65.35	88.91	154.19	206.24	219.52	221.85	121.38	122.96	69.83	63.14	72.38	49.11	1454.85	961.77
	Percentage	4.49%	6.11%	10.60%	14.18%	15.09%	15.25%	8.34%	8.45%	4.80%	4.34%	4.98%	3.38%	100.00%	66.11%
	R (10^8 m^3)	16.83	21.44	43.27	64.78	75.82	83.18	45.24	35.68	27.49	21.73	18.00	15.82	469.27	332.19
	Percentage	3.59%	4.57%	9.22%	13.80%	16.16%	17.73%	9.64%	7.60%	5.86%	4.63%	3.84%	3.37%	100.00%	70.79%
	S (10^4 t)	7.42	14.75	66.40	116.32	135.22	158.44	51.31	38.39	28.25	15.75	6.58	4.67	643.51	527.94
	Percentage	1.15%	2.29%	10.32%	18.08%	21.01%	24.62%	7.97%	5.97%	4.39%	2.45%	1.02%	0.73%	100.00%	82.04%
Xiashan	*P* (mm)	63.82	104.76	165.46	192.11	228.70	224.42	117.11	144.76	109.83	69.82	53.26	44.66	1518.72	1016.94
	Percentage	4.20%	6.90%	10.89%	12.65%	15.06%	14.78%	7.71%	9.53%	7.23%	4.60%	3.51%	2.94%	100.00%	66.96%
	R (10^8 m^3)	4.50	6.09	12.78	19.13	23.12	27.80	12.54	9.89	7.74	5.66	4.37	3.87	137.49	100.23
	Percentage	3.27%	4.43%	9.30%	13.92%	16.82%	20.22%	9.12%	7.19%	5.63%	4.12%	3.18%	2.81%	100.00%	72.90%
	S (10^4 t)	2.78	4.65	19.12	35.58	44.14	57.95	14.10	11.22	8.09	2.97	2.14	1.43	204.18	171.09
	Percentage	1.36%	2.28%	9.37%	17.43%	21.62%	28.38%	6.91%	5.50%	3.96%	1.45%	1.05%	0.70%	100.00%	83.79%
Bashang	*P*(mm)	70.87	91.80	162.86	176.23	213.39	202.33	107.65	154.29	83.90	52.26	41.01	30.25	1386.83	937.79
	Percentage	5.11%	6.62%	11.74%	12.71%	15.39%	14.59%	7.76%	11.13%	6.05%	3.77%	2.96%	2.18%	100.00%	67.62%
	R (10^8 m^3)	2.61	2.94	5.36	7.64	8.83	10.34	6.21	5.46	4.45	3.42	2.91	2.50	62.67	42.93
	Percentage	4.17%	4.70%	8.55%	12.18%	14.09%	16.50%	9.91%	8.71%	7.11%	5.45%	4.64%	3.99%	100.00%	68.51%
	S (10^4 t)	1.03	2.13	10.07	17.40	20.17	25.00	7.99	6.86	5.64	3.16	1.04	0.57	101.06	86.21
	Percentage	1.02%	2.11%	9.97%	17.22%	19.96%	24.73%	7.90%	6.79%	5.58%	3.13%	1.03%	0.56%	100.00%	85.31%
Julongtan	*P* (mm)	69.65	105.54	181.73	190.14	234.56	228.95	119.85	152.24	103.01	68.32	54.85	48.95	1557.79	1028.76
	Percentage	4.47%	6.77%	11.67%	12.21%	15.06%	14.70%	7.69%	9.77%	6.61%	4.39%	3.52%	3.14%	100.00%	66.04%
	R (10^8 m^3)	2.04	2.56	5.31	8.31	9.58	11.61	5.60	5.11	4.22	2.83	2.15	1.85	61.16	44.42
	Percentage	3.34%	4.19%	8.68%	13.60%	15.66%	18.98%	9.16%	8.35%	6.90%	4.62%	3.52%	3.02%	100.00%	72.64%
	S (10^4 t)	1.29	3.16	13.72	23.75	25.81	31.33	7.71	10.76	6.43	1.96	0.74	0.54	127.21	105.80
	Percentage	1.01%	2.48%	10.78%	18.67%	20.29%	24.63%	6.06%	8.46%	5.05%	1.54%	0.58%	0.43%	100.00%	83.17%
Hanlinqiao	*P* (mm)	72.14	107.26	181.37	202.72	244.06	227.65	133.00	130.32	98.15	72.88	56.97	47.52	1574.04	1035.89
	Percentage	4.58%	6.81%	11.52%	12.88%	15.51%	14.46%	8.45%	8.28%	6.24%	4.63%	3.62%	3.02%	100.00%	65.81%
	R (10^8 m^3)	0.82	1.09	2.11	3.22	3.79	4.62	2.26	1.71	1.30	1.05	0.85	0.74	23.56	16.90
	Percentage	3.49%	4.62%	8.97%	13.68%	16.09%	19.60%	9.58%	7.27%	5.53%	4.44%	3.59%	3.15%	100.00%	71.74%
	S (10^4 t)	1.06	2.45	8.38	15.16	17.99	22.83	7.58	6.43	4.07	2.18	1.01	0.58	89.72	74.06
	Percentage	1.18%	2.74%	9.34%	16.90%	20.06%	25.44%	8.44%	7.17%	4.54%	2.43%	1.12%	0.65%	100.00%	82.54%



(**a**)

Figure 2. *Cont.*



(**b**)

Figure 2. (**a**) Observed annual hydro-meteorological variables in the upstream of Ganjiang River basin. (**b**) Observed annual hydro-meteorological variables in the midstream and downstream of Ganjiang River basin. Note: The solid and hollow markers represent annual streamflow and sediment discharge, respectively. The horizontal solid and dashed lines are the mean values and trend lines, respectively.

Table 3. The Mann–Kendall test (Z statistic) for the annual and seasonal changes of precipitation, streamflow, and sediment discharge.

Variables	Stations	Annual	Seasonal			
			January–March	April–June	July–September	October–December
Precipitation	Bashang	−0.22 NS	1.37 *	−1.25 NS	−1.08 NS	0.66 NS
	Xiashan	0.59 NS	0.08 NS	−1.86 **	0.88 NS	−2.15 **
	Julongtan	−0.15 NS	0.67 NS	−1.02 NS	1.33 *	−1.52 *
	Hanlinqiao	0.67 NS	−1.52 *	−0.62 NS	1.62 *	−1.33 *
	Ji'an	0.47 NS	1.43 *	−0.14 NS	1.03 NS	−0.27 NS
	Xiajiang	1.14 NS	-	-	-	-
	Waizhou	0.62 NS	1.48 *	0.13 NS	0.55 NS	0.28 NS
Streamflow	Bashang	0.54 NS	0.05 NS	-1.30 *	1.90 **	0.28 NS
	Xiashan	0.44 NS	0.87 NS	−0.90 NS	2.00 **	0.70 NS
	Julongtan	0.80 NS	0.69 NS	−0.44 NS	1.59 *	−0.55 NS
	Hanlinqiao	0.69 NS	1.41 *	-1.41 *	2.02 **	1.25 NS
	Ji'an	0.57 NS	1.19 NS	−0.70 NS	1.72 **	0.89 NS
	Xiajiang	0.68 NS	-	-	-	-
	Waizhou	0.59 NS	1.10 NS	−1.00 NS	1.20 NS	0.80 NS
Sediment	Bashang	−4.27 **	-1.42 *	−3.40 **	−1.64 **	−2.19 **
	Xiashan	−2.98 **	−1.54 *	−3.11 **	−0.84 NS	−1.54 *
	Julongtan	−1.94 **	0.42 NS	−1.29 *	0.50 NS	−1.71 **
	Hanlinqiao	−4.68 **	−1.91 **	−4.43 **	−1.22 NS	−1.25 NS
	Ji'an	−5.60 **	−2.43 **	−5.57 **	−4.02 **	−2.47 **
	Xiajiang	−5.30 **	-	-	-	-
	Waizhou	−6.03 **	−1.84 **	−5.29 **	−3.31 **	−1.44 *

**: significant at p = 0.05; *: significant at p = 0.1; NS: not significant. -: no data.

3.3. Abrupt Changes in Sediment Discharge

The non-parametric Pettitt method was used to detect the transition years when significant changes began. The change-point analysis results for annual sediment discharge showed that transition years could be detected (p = 0.05) at all stations, while no change-point year could be detected for annual streamflow at any station (Figure 3). K_T statistics of Pettitt's test for sediment discharge at seven stations were significant, and all of their transition years were determined to be significant at p = 0.05, but different transition years were found at different stations. Specifically, sediment discharge at Bashang, Xiashan, Julongtan, Hanlinqiao, Ji'an, Xiajiang, and Waizhou stations decreased significantly after the transition years at 1994, 1998, 2002, 1985, 1992, 1992, and 1989, respectively (Figure 3). In other words, the significant decline of sediment discharge occurred in the 1980s in both Hanlinqiao and Waizhou stations, and the 1990s in Bashang, Xiashan, Ji'an, and Xiajiang stations, and 2002 in Julongtan station.

3.4. Impacts of Precipitation and Human Interference

Previous studies have identified global and regional climate change (mainly changes in regional precipitation) and local human activity as the two main factors impacting basin hydrology [7]. In this study, the double mass curve of precipitation–sediment before the transition years and its corresponding regression equations were used to caculate the annual sediment discharge values after the transition years. The difference between calculated values in different periods is the impact of precipitation variation, while differences between calculated and observed values in the same period identify impacts due to human intervention (Figure 4). The detailed results from this study area are given in Table 4. Results showed that compared with the calculated cumulative sediment discharge (Sc), observed cumulative sediment was 21.55%, 13.33%, 13.12%, 27.23%, 30.07%, 30.17%, and 31.10% lower at Bashang, Xiashan, Julongtan, Hanlinqiao, Ji'an, Xiajiang, and Waizhou stations, respectively. In other words, after the transition year, the sediment discharge of these hydrological stations had declined at varying degrees, and the average degree of decline at stations of midstream and downstream were almost the same (30.1%), which were larger than that of upstream (18.8%).

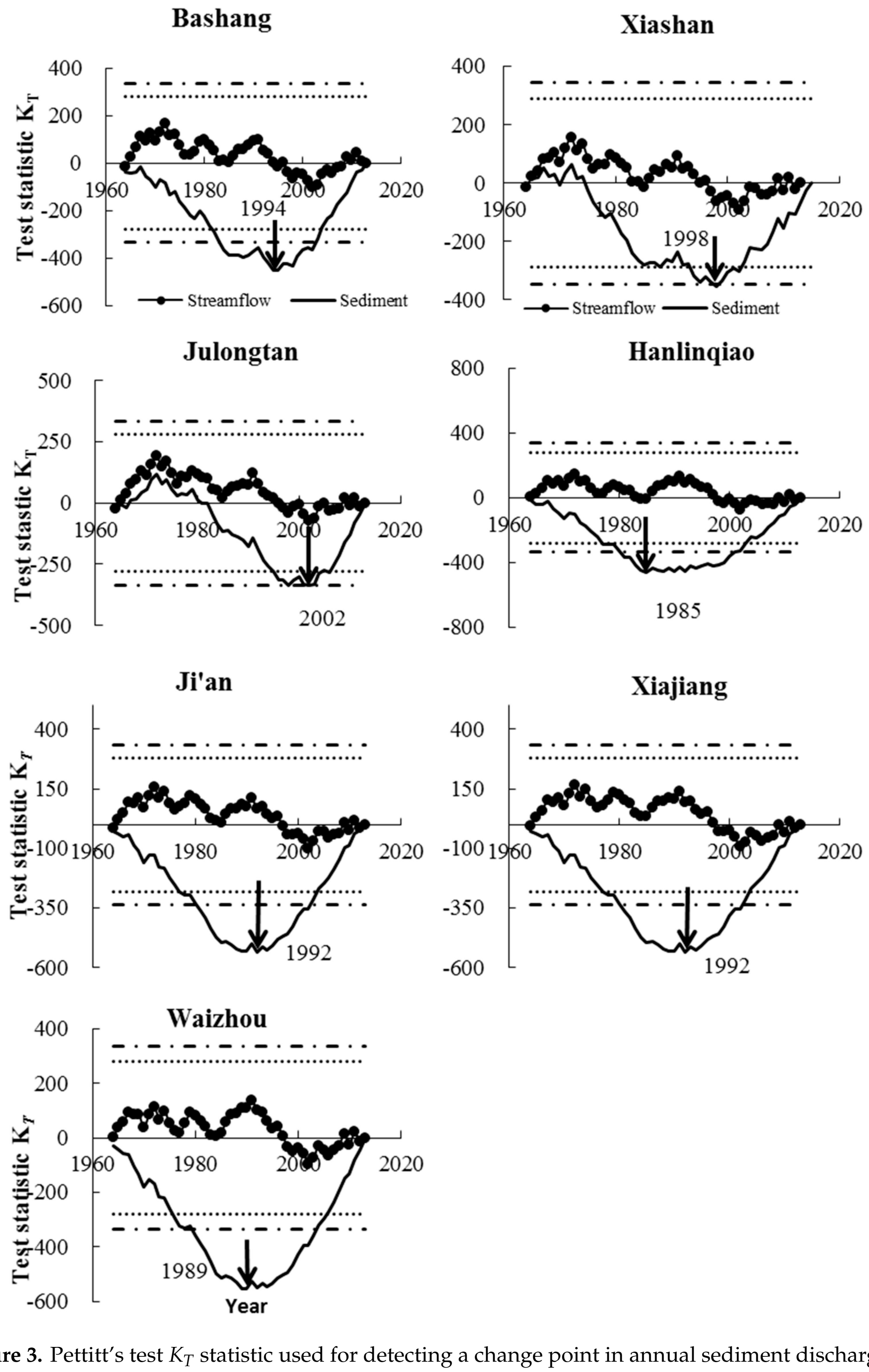


Figure 3. Pettitt's test K_T statistic used for detecting a change point in annual sediment discharge of hydrological stations during 1964–2013 on the Ganjiang River basin. Note: The black arrow indicates the change-point year, and the horizontal lines represent the significance levels of 99% (dotted) and 95% (dash-dot), respectively.

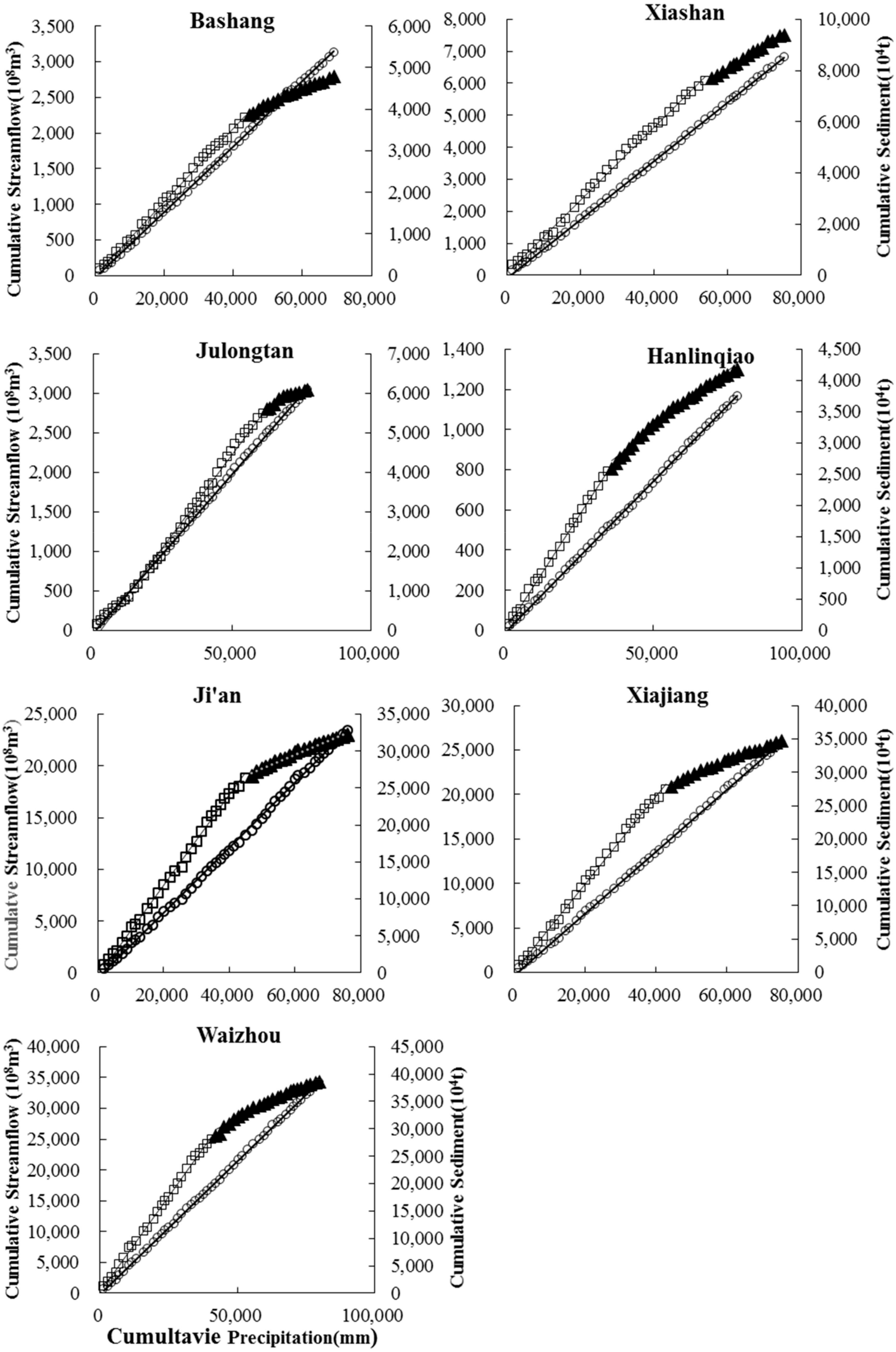


Figure 4. Double mass curves of precipitation–streamflow and precipitation–sediment at seven hydrological stations with sediment data in the Ganjiang River basin. Note: Here, ○ represents cumulative precipitation–streamflow, □ and ▲ represents cumulative precipitation–sediment before and after the transition year, respectively.

Table 4. The observed and calculated cumulative sediment discharge at hydrological stations in the Ganjiang River basin.

Stations	Regression Equation	S_c (10^4 t)	S_o (10^4 t)	$S_c - S_o$ (10^4 t)	$100 \times (S_c - S_o)/S_c$ (%)
Bashang	$\sum S_b = 0.088\sum P_b + 1.49(R^2 = 0.998, N = 31)$	6094.97	4781.36	1313.61	21.55
Xiashan	$\sum S_{xs} = 0.143\sum P_{xs} + 76.62(R^2 = 0.998, N = 35)$	10,839.49	9394.82	1444.67	13.33
Julongtan	$\sum S_j = 0.094\sum P_j - 256.17(R^2 = 0.994, N = 39)$	7007.48	6087.97	919.52	13.12
Hanlinqiao	$\sum S_h = 0.073\sum P_h + 8.88(R^2 = 0.999, N = 22)$	5743.65	4179.38	1564.27	27.23
Ji'an	$\sum S_j = 0.61\sum P_j - 391.07(R^2 = 0.998, N = 29)$	46,008.36	32,175.43	13,832.43	30.07
Xiajiang	$\sum S_{xj} = 0.66\sum P_{xj} + 92.76(R^2 = 0.998, N = 29)$	49,807.30	34,778.40	15,028.90	30.17
Waizhou	$\sum S_w = 0.7\sum P_w + 252.13(R^2 = 0.999, N = 26)$	55,929.87	38,533.39	17,396.48	31.10

Note: S_c, calculated cumulative sediment discharge; S_o, observed cumulative sediment discharge; $S_c - S_o$, reduction of cumulative sediment discharge after transition years in the Ganjiang River (N = years, $\sum P$ = observed cumulative precipitation).

Table 5. Impact of precipitation and human intervention on sediment discharge decline after the change-point year at five stations in Ganjiang River.

Station	Period	$\overline{S_{obs}}$	$\overline{S_{cal}}$	$\triangle S'$ (10^4 t)	Impact of Precipitation (%)	Impact of Human (%)
Bashang	Before 1994	122.27				
	After 1994	52.15	119.39	70.12	4.11	95.89
Xiashan	Before 1998	216.44				
	After 1998	121.29	204.05	95.14	13.02	86.98
Julongtan	Before 2002	140.79				
	After 2002	86.49	135.56	86.49	6.04	93.96
Hanlinqiao	Before 1985	115.35				
	After 1985	58.63	113.67	56.72	2.97	97.03
Ji'an	Before 1992	907.62				
	After 1992	278.79	905.68	628.83	0.31	99.69
Xiajiang	Before 1992	946.31				
	After 1992	349.30	1025.83	597.00	−13.31	113.31
Waizhou	Before 1989	1081.37				
	After 1989	434.07	1135.41	647.30	−8.35	108.35

Note: $\overline{S_{cal}}$, average calculated annual sediment discharge; $\overline{S_{obs}}$, average observed annual sediment discharge; $\triangle S'$, reduction in average observed sediment discharge between the period before and after the transition years in the Ganjiang River basin on the Ganjiang River (N = years, p = precipitation).

Moreover, the fitting of accumulated streamflow and precipitation is very well, but every regression line of accumulated sediment discharge observations had a clear breakpoint as the transition years identified by Pettitt's method, which indicate that rainfall is the main cause of runoff change, but compared with the rainfall variation, human activity was the more dominant factor causing the sediment discharge decline after the transition year (Table 5). For most of stations, the rates at which human activities contributed to reductions in sediment discharge at Bashang, Hanlinqiao, Ji'an, Xiajiang, and Waizhou were greater than 95%, and some were even greater than 100% (e.g., 113.32% at Xiajiang), which was probably caused by the increased precipitation and decreased sediment discharge. The contribution rate of human activities to sediment discharge decline at Xiashan was 86.98%, but this was still much larger than the contribution rate of precipitation.

3.5. Driving Factors of Sediment Discharge Change

Many studies have shown that the great improvement of vegetation cover and construction of large and medium reservoirs are the important factors significantly reducing sediment discharge [8,9,13,31]. The statistical yearbook of Jiangxi province in 2016 showed that the vegetation cover of Ganjiang River basin had increased from 37.3% of 1965 to 63.1% of 2015. During this period, there has been a significant increase of the vegetation cover in the last 30 years, except for a small decrease in 1965–1985 (Table 6). Before the 1980s, due to the combined effects of natural factors such as high-intensity rain storms in the flood season, topography, geology, and soil, etc., and man-made vegetation destruction such as damaging forests to reclaim land and cutting down the forest and grass as firewood for cooking and steelmaking fuel, etc., make the basin of Ganjiang River (especially its upstream area) one of the most serious soil erosion areas in southern China [22,32]. Then, recognizing the seriousness of soil erosion, the government had lanuched long-term and high-input national water-and-soil conservation measures after the 1980s, which greatly increased the vegetation cover and improved the ecological environment of Ganjiang River basin [22].

Table 6. The change of forest coverage (%) in Ganjiang River Basin in the past decades.

Year	1965	1975	1985	1995	2005	2015
Forest coverage	37.3	36.5	33.1	50.9	60.05	63.1

Note: Table's data information comes from statistical yearbook of Jiangxi province in 2016.

Previous studies have shown that water conservancy facilities (especially reservoirs) had a great influence on runoff and sediment transport in the five tributaries of Poyang Lake, which is also responsible for the reduction of sediment transport at most hydrological stations in the Poyang Lake Basin [23]. In this study, reservoir construction times were divided into three periods: Before 1980, 1981–2000, and 2000–2013. Statistical results showed that in the past decades, there were 145 large and medium-sized reservoirs almost equally distributed in the upper, middle, and lower reaches of the Ganjiang River basin, and their total drainage area was 21,4821.45 km^2 (Table 7). The 51 reservoirs in the midstream area occupied 52% of the drainage area of the entire region. The 48 reservoirs in the upstream area occupied 45% of the drainage area. In contrast, the 46 reservoirs in the downstream area only occupied 3% of the total drainage area, which showed that there were fewer large reservoirs constructed in this area. The period "before 1980" mainly saw construction of numerous medium-sized reservoirs, and the total water-collecting area was 16,202.61 km^2, almost equally distributed in the three main reaches. During the 1981–2000 period, the number of reservoirs was greatly reduced, but the total water-collecting area was more than three times greater than during the "before 1980" period, with 71% of the drained area found in the middle reaches of the drainage area. During the 2001–2013 period, the number of reservoir was also much fewer than during the "before 1980" period, and mainly concentrated on the construction of large reservoirs in the middle and upper reaches (especially the Gongshui River basin).

Take Julongtan station for example, a dramatic decline was observed in the sediment discharge after 2002, which corresponded to the construction of large reservoirs during the 2001–2013 period (Figure 3, Table 7). Although no reservoirs were built for the Hanlinqiao station in Xingguo county after 1980, the region saw a continuation (twice launched) of 10 years of national water-and-soil conservation measures, which included afforestation, construction of sand collection dams, planting soil and water conservation forests, economic forestry, and planting grasses and fruit-bearing trees [22]. Moreover, Guo et al. [17] calculated land-use classification proportions for the total area in the six counties of the Gongshui River basin between 1992 and 1997, and found the the forest and grass coverage of all cities was increasing. In Xingguo County, this increase in forest and grass coverage was mainly concentrated at the end of the first period of national water and soil conservation measures.

Table 7. Characteristics of large and medium-sized reservoirs constructed in the past decades in the Ganjiang River Basin.

Station	Tributary (Including Counties)	Before 1980 Number of Reservoirs	Before 1980 Drainage Area (km^2)	1981–2000 Number of Reservoirs	1981–2000 Drainage Area (km^2)	2001–2013 Number of Reservoirs	2001–2013 Drainage Area (km^2)	Grand Total Number of Reservoirs	Grand Total Drainage Area (km^2)
Bashang	Zhangshui (Chongyi, Dayu, Shangyou, Nankang)	5	2938	5	9835	3	1667	13	14,440
Xiashan	Gongshui (Anyuan, Xunwu, Huichang, Ruijin, Yudu, Ningdu, Shicheng)	8	1129	4	4016	8	61,049	20	66,193
Julongtan	Taojiang (Quannan, Longnan, Xinfeng, Ganxian)	8	649	2	502	3	14,071	13	15,222
Hanlinqiao	Pingjiang (Xingguo)	2	965	0	0	0	0	2	965
Xiajiang Ji'an	All counties in Ji'an and Le'an in Fuzhou	33	5071	10	38,758	8	67,291	51	111,119
Waizhou	All counties in Xinyu and Yichun (except Fengcheng)	39	5451	6	1416	1	15	46	6883
	Grand total	95	16,203	27	54,526	23	144,093	145	214,821

Note: Table's data information comes from the water conservancy census of Jiangxi Province in 2013.

4. Conclusions

In this study, several statistical methods were applied to investigate the changing trends, transition years, and driving forces and their contribution rates to precipitation, streamflow, and sediment discharge changes in the Ganjiang River basin using continuous long time series. The results demonstrated a significant reduction in annual sediment discharge over time ($p > 0.05$) at all hydrological stations, but no significant trends for either precipitation or streamflow were found. When analyzed by season, significant increasing and decreasing trends were found for both precipitation and streamflow, but only decreasing trends were found for sediment discharge. Moreover, the significant decline of sediment discharge occurred in the 1980s in both Hanlinqiao and Waizhou stations, and the 1990s in Bashang, Xiashan, Ji'an, and Xiajiang stations, and 2002 in Julongtan station. The average degree of decline at stations of midstream and downstream were 30.1%, which were much larger than 18.8% of upstream.

The abrupt changes in the trends of sediment discharge in this region were attributed to both precipitation and human activity, but human activities (especially the vegetation cover change and reservoir construction) were the most plausible factors responsible for sediment discharge changes in the Ganjiang River basin since the 1980s. In the past five decades, the vegetation cover in this area increased by almost 30%. There were 145 large and medium-sized reservoirs almost equally distributed in the upper, middle, and lower reaches of the drainage area, but 52%, 45%, and 3% of the total 214,821.45 km^2 water-collecting area were occupied by the reservoirs located at midstream, upstream, and downstream regions of the Ganjiang River basin. Moreover, the 'before 1980' period saw construction of numerous medium-sized reservoirs, while only a small number of both large and medium-sized reservoirs were constructed during the 1981–2000 period, and the 2000–2013 period only saw the construction of a few large reservoirs.

In general, this comprehensive analysis based on long-term time series of the hydro-climatic data provides useful insights for watershed management decision-makers to recognize that precipitation and human activities are the main driving factors of runoff and sediment discharge changes of the Ganjiang River during the last five decades, respectively. Comprehensive measures for soil and water conservation by increasing forest coverage and building large and medium-sized reservoirs can effectively reduce sediment discharge in river basins. Moreover, as an example of river evolution under global change environment, study on the changes of streamflow and sediment and its driving force in Ganjiang River basin could provide scientific basis for the control of soil erosion and the management of water resources in Ganjiang River, as well as for the related research of Poyang Lake and the Yangtze River basin. Specifically, the reduced sediment discharge would cause land degradation and river regime evolution like river channel slices downwards, which will influence the ecological balance of terrestrial and river ecosystems, and maybe even exacerbate the seasonal drought and ecological hazards in Poyang Lake Basin.

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