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Response of Sediment Load to Hydrological Change in the Upstream Part of the Lancang-Mekong River over the Past 50 Years

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Abstract: Sediment load and its response to the variations of the hydrological elements are important for the healthy utilization of a river. In this study, the response of sediment load to hydrological change was explored in the upstream part of the Lancang-Mekong River, a major transboundary river originating from the Tibetan Plateau and running through China, over the past 50 years. A sediment rating curve for the Jiuzhou Station was developed based on the available SSC-Q (suspended sediment concentration (SSC) and flow) data and trends in annual precipitation, runoff, peak flow (PF), low flow (LF), maximum water level (MWL), and sediment load were analyzed from 1957 to 2006. The correlation analysis method and Random Forest (RF) were adopted to qualitatively and quantitatively quantify the contribution of each hydrological element to the sediment load change. Results indicated that both the runoff and sediment load showed a significantly upward trend, especially after 1979, at the 95% confidence level. The sediment load had significantly positive correlations with runoff, PF, and MWL at the 99% confidence level, respectively. In particular, the sediment load had the largest significant positive correlation with runoff since 1980. Runoff had the largest variable importance to the sediment load change, followed by PF, MWL, precipitation, and LF. The increasing trend in the sediment load was mainly attributed to the increase of runoff in the upstream part of the Lancang-Mekong River since the mid-1980s.

Keywords: Sediment load; random forest; hydrological response; Lancang-Mekong River

1. Introduction

Variation of suspended sediment load in a river or reservoir has received many attentions in the fields of water and soil resource planning program, the design and operation of hydraulic projects, and the protection of the ecosystem system [1–4]. Investigation of suspended sediment discharge change is very important for hydroelectric power generation, reservoir design, irrigation, and the regulation of water use policies, etc. [5,6]. Considerable research has been conducted on how factors control sediment yield in a basin (e.g., land use change [7], land slopes [8], weather types [9], and precipitation or other climatic variables change [10–14]), the spatial-temporal change of sediment concentration and Runoff-Sediment Relationship (RSR) [15,16], and the scale effect of RSR [17–19]. These studies provided important trend data and are useful for understanding sediment yield change associated with climate and land use changes. In fact, long-term suspended sediment yield is affected by different hydrologic regimes and actual suspended sediment concentration varies during different river flow conditions. For instance, Rosen and Xu [20] found that the suspended sediment concentration (SSC) were maximized during high flow and intermediate flow stages, and peak flow stages had the highest discharge but significantly lower SSC in the lower Mississippi River. However, the investigation of the relationship between the suspended sediment and related hydrological elements is still insufficient. Particularly, suspended sediment in Alpine streams like the Lancang-Mekong River is influenced by various climatic parameters and hydrological processes with the hydrological regimes more sensitive [21].

The Lancang-Mekong River, the largest international river in Asia, originates from Guyong-Pudigao Creek and runs through China, Laos, Myanmar, Thailand, Vietnam, and Cambodia before finally discharging into the South China Sea in Southern Vietnam [22]. It originates from the Tibetan Plateau and has received much attention in recent years, largely owing to its flow through many countries and a chain of cascade hydroelectric dams constructed in the river [22]. As an international river, its changes of runoff, precipitation, and suspended sediment discharge are important to the international community. From the perspective of runoff and sediment, a number of studies have been carried out mainly focusing on the spatial and temporal changes in runoff and suspended sediment discharge [23–25] and the comprehensive impact of hydropower development, monsoons, and El Niño-Southern Oscillation (ENSO) on runoff and sediment changes [26,27]. In the Lancang River, for instance, significant climate warming and an increase of precipitation were found at both the annual and seasonal scales [28]; multi-timescale characteristics of the variations of the annual water level were found in the Lancang River [29], and the monthly streamflow at Jiuzhou Station was projected to range from a 27.9% decrease to a 158.4% increase during 2011–2095 [30]. These hydrological changes will affect suspended sediment discharge of the Lancang-Mekong River, which is important for the ecological protection, the downstream dams' operation, flood control along the river, and even the international relations between Southeast Asian countries. However, suspended sediment discharge response to hydrological change in the Lancang-Mekong River still remains unclear. How do the suspended sediment load and hydrological elements change in the upstream part of the Lancang-Mekong River? What is the quantitative importance of the hydrological elements such as precipitation, runoff, water level and flood event to the suspended sediment load?

Given the abovementioned issues of changing characteristics of the main hydrological elements including sediment load and the correlation of each hydrological element to the sediment load in the upstream part of the Lancang-Mekong River, this study focused on the trend of each hydrological element with the linear regression analysis method and the quantitative correlation of each hydrological element with suspended sediment load. The linear regression analysis method is a simple parametric approach and has been widely used to detect time series trends, with the limitations of non-normal data and being affected with outliers. The two main contributions are as follows: (1) it explored the quantitative and qualitative correlations of sediment load with the main related hydrological elements (e.g., runoff, precipitation and peak flow) in the Lancang River, and (2) it investigated the changing characteristics of sediment load and its underlying causes in the upstream part of the Lancang-Mekong River. This study helps to give us a better understanding of how river channel evolution and sedimentation change under climate change in the upstream part of the Lancang-Mekong River.

2. Study Area and Dataset

2.1. Study Area

The total basin area of the Lancang-Mekong River is over 810,000 km^2, with a total primary river length of approximately 4880 km. The upstream part of the Mekong River in China is called the Lancang River with a basin area of 174,000 km^2 and length of approximately 2161 km. Currently, 14 cascade hydroelectric dams have been completed along the main river channel to utilize its extremely rich water energy resources [22,27]. The study area is the upstream part of the Lancang-Mekong River from the Jiuzhou Station in Yunnan Province, involving 15 planned cascade hydroelectric dams (Figure 1). Jiuzhou Station has a drainage area of 88,051 km^2 with an annual mean discharge of 29.5 billion m^3 and is 774 km from the downstream exit. The elevation of the ground is 1295 m. At the current stage, the 15 planned dams in the upstream Lancang-Mekong River are still part of a feasibility study, and the influence of dams on the upstream suspended sediment discharge is not apparent. Hence, five hydrological elements including precipitation, runoff, peak flow (PF), low flow (LF), and maximum water level (MWL) were chosen to investigate their contributions to the suspended sediment load change in the upstream part of the Lancang-Mekong River. PF and LF are the annual maximal flow and minimum flow, respectively. All the variables were calculated at annual scale based on the observed monthly data.

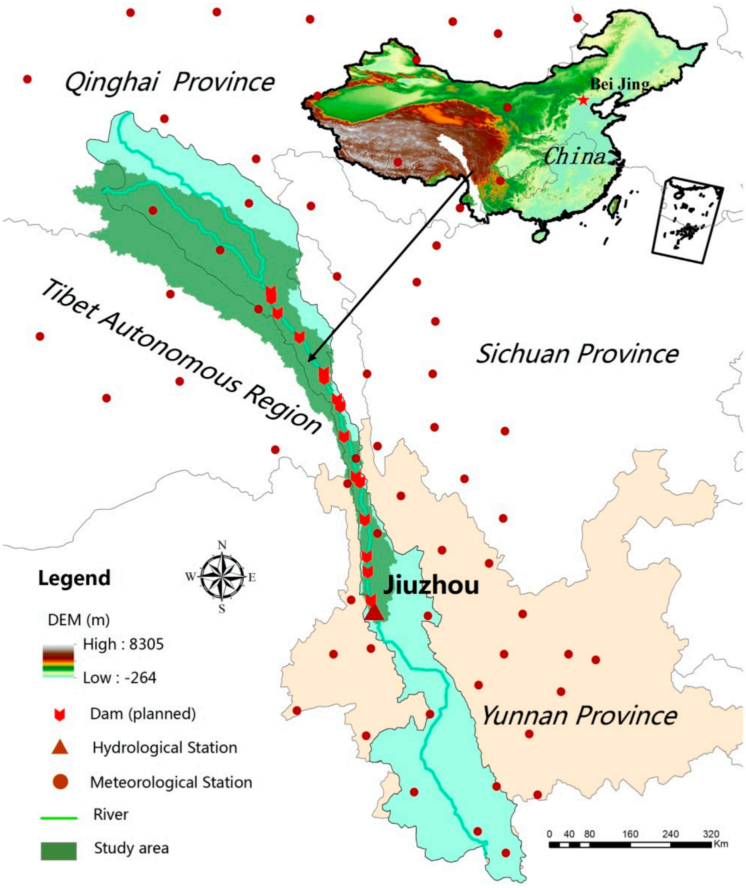


Figure 1. Location of the Jiuzhou Station and proposed dams in the upstream part of the Lancang-Mekong River.

2.2. Dataset

The monthly precipitation, runoff, PF, LF, MWL, and suspended sediment discharge data of Jiuzhou Station for the years 1957–2006 were provided by the Hydrological Bureau of Yunnan Province. In the current dataset, the suspended sediment discharge was calculated by mean vertical sediment concentration multiplied by weighted flow; the mean vertical sediment concentration is measured using the depth-integrated method; the sample frequency is 5 once a month for the mean sediment concentration at the vertical; in particular, in the flood period, the sample frequency is 7 once a month. Runoff was calculated with the single curve method and the curve standard deviation ranges from 1.9 to 2.7%. The maximum water level was observed by the digital water-level recorder; precipitation was observed by 29 rain gauges with rainfall recorder. The Thiessen Polygons (TP) method was used to interpolate the average precipitation for the entire area based on the observed precipitation records of the 29 rain gauges. Power China Guiyang Engineering Corporation Limited provided data for the cascade hydroelectric dams along the main channel of the Lancang-Mekong River. Missing monthly suspended sediment discharge data accounted for less than 0.2% of the total data over the 50 years, and the correlational analysis method was used to estimate the missing data based on the reference stations that had valid data. Figure 2a–c show the monthly changes of the suspended sediment discharge, runoff, PF, and MWL of wet, normal, and dry flow years at Jiuzhou Station, respectively. MWL in a dry year (Figure 2c) varied a less wide range than that in a wet (Figure 2a) and normal year (Figure 2b).

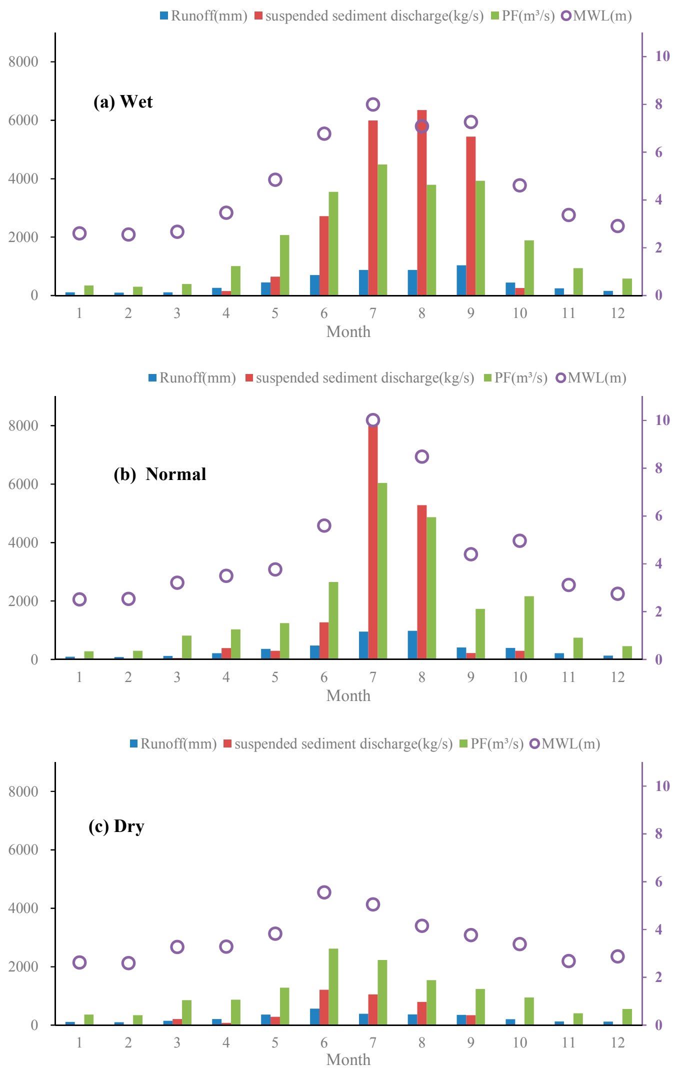


Figure 2. The suspended sediment discharge, runoff, peak flow (PF), low flow (LF), and maximum water level (MWL) of wet, normal, and dry flow years at Jiuzhou Station.

3. Methodology

In this study, given that continuous data are unavailable, the sediment rating curve approach was used to estimate suspended sediment concentration (SSC) values. To learn about the changing characteristics of the sediment load and hydrological elements in the upstream part of the Lancang-Mekong River, we used the linear regression analysis method for the purpose of detecting trends. For a better and convictive illustration of the response of sediment load to hydrological change, Random Forest was employed to quantify the quantitative importance of each hydrological element to the sediment load change compared to the correlation analysis of each hydrological element with sediment load.

3.1. Load estimation

A sediment rating curve has been widely used to estimate SSC values when continuous data are unavailable [31,32]. A linear ordinary least square regression to the variables in log space is most commonly applied to develop the following equation [31,32]:

$$\text{logSSC} = \log\alpha + \beta\text{logQ} \quad (1)$$

where α and β are the constants of the linear regression.

To reduce the statistical bias caused by the de-transformation of the variables from log space to normal space, a correction factor (CF) was proposed to multiply the resulting loads as follow [33]:

$$\text{CF} = \exp\left(2.651s^2\right) \quad (2)$$

where s^2 is the mean square error of the log-transformed regression.

In the current study, a sediment rating curve for the Jiuzhou Station was developed, and the rating curve was used to calculate annual sediment load for the purpose of determining the relations of the sediment load with the five hydrological elements.

3.2. The Linear Regression Analysis

Linear regression was the first type of regression analysis to be studied rigorously and to be used extensively in practical applications [34]. This was because models that depend linearly on their unknown parameters are easier to fit than models that are non-linearly related to their parameters and the statistical properties of the resulting estimators are easier to determine. Moreover, it is simple and clear and does not require a control group, experimental design, or a sophisticated analysis [35]. In statistics, linear regression is a linear approach for modelling the relationship between a scalar dependent variable y and one or more explanatory variables (or independent variables) denoted as x [36]. In general, linear regression models are often fitted using the least squares approach, and the straight line can be calculated by Equation (3) [34].

$$y_i = a + bx_i \quad (3)$$

where a is the regression constant and b is the regression coefficient, and a, b is defined by Equation (4).

$$\begin{cases} b = \dfrac{\sum_{i=1}^{n} x_i y_i - \frac{1}{n}\left(\sum_{i=1}^{n} x_i\right)\left(\sum_{i=1}^{n} y_i\right)}{\sum_{i=1}^{n} x_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} x_i\right)^2} \\ a = \overline{y} - b\overline{x} \end{cases} \quad (4)$$

where $\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$, $\overline{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$ by using the relationship between the regression coefficient b and correlation coefficient r, we can define correlation coefficient r by Equation (5).

$$r = \sqrt{\frac{\sum_{i=1}^{n} x_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} x_i\right)^2}{\sum_{i=1}^{n} y_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} y_i\right)^2}} \quad (5)$$

Given the above advantages, in this study, the linear regression method was chosen to analyze whether hydrological elements had increased or decreased over the period 1957–2006 and to find the correlation of sediment load with the hydrological elements. The correlation helps to find the main driving factors of the sediment load change.

3.3. Random Forest

Random Forest (RF) is a form of statistical learning theory proposed in the early 21st century [37]. It has advantages in preventing over fitting and has a high tolerance for abnormal values and noise. In addition, it is also a good solution for multivariable prediction [38]. RF is a combined model consisting of multiple decision trees [39]. Its rationale is that the multiple samples are extracted from the original sample by bootstrap resampling, and then each bootstrap sample is modeled by a single decision tree. Finally, the prediction results are obtained by voting or averaging from all the classification trees. Random Forests (RF) have been an increasingly popular machine learning algorithm in medicine, bioinformatics, finance, and so on for the advantages of prediction and classification with an exceptionally attractive performance related to the good quality of each tree and the small correlation among the trees of the forest [40].

Variable Importance (VI), defined by Equation (6), is one of the main applications of RF and can be calculated by permuting an out-of-bag (*OOB*) sample [39]. For each tree, the estimated error on the *OOB* portion of the samples is recorded (error rate for classification, and mean square error (MSE) for regression). Then, the same is done after permuting each predictor variable. The differences between the two prediction errors are then averaged over all trees and normalized by the standard deviation of the differences [38].

$$VI(X_i) = \frac{1}{N}\sum_k^N \left(errOOB_k^i - errOOB_k\right) \quad (6)$$

where $VI\ (X_i)$ is the importance of the variable X_i, N is the size of trees of RF, $errOOB_k$ is the estimated error of the *OOB* sample set of tree k, and $errOOB_k^i$ is the same as $errOOB_k$, but for the *OOB* sample set that is permuted randomly of tree k. In this study, the RF was applied to calculate the variable importance of precipitation, runoff, PF, LF, and MWL, which helps to find the main driving factors that make the sediment load change.

4. Results and Discussion

4.1. Rating Curve Development

A sediment rating curve for the Jiuzhou Station was developed based on all the available SSC-Q data and applied to the flow record for the annual sediment load estimation. Figure 3 presents the rating curve generated for the upstream part of the Lancang-Mekong River. The regression line of the log-linear rating curve includes the correction factor (CF). The α and β parameters for Equation (1) are presented in Table 1 together with the CF and coefficient of determination (R^2) for the rating curve equation. The R^2 value for the River is 0.34, the regression was found to be significant at the 0.5% level (p = 0.005). Given this, the log-linear rating curve was used to produce annual sediment load.

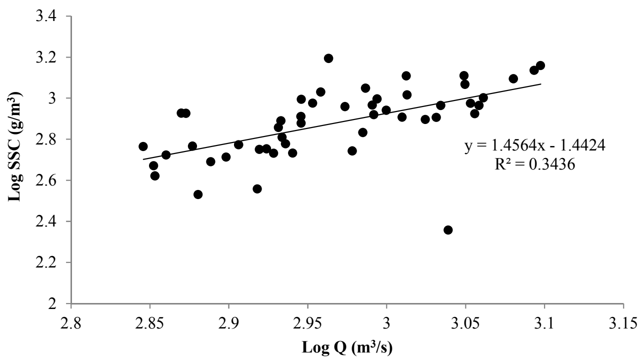


Figure 3. Rating curve for the Jiuzhou Station.

Table 1. Rating coefficients for Equation (1), correction factor (CF), coefficient of determination (R^2), and significance (p-value) for the Jiuzhou Station.

α	β	CF	R^2	p-Value
0.036	1.456	1.052	0.34	<0.005

4.2. Trends in Annual Precipitation, Runoff, MWL, PF, LF, and Sediment Load

Figure 4 shows the time series of annual precipitation, runoff, PF, LF, MWL, and sediment load in the Jiuzhou Station, mainly for the purpose of intuitive comparison of the changes of the six hydrological elements over the past 50 years. According to Figure 4, precipitation had a change rate of 8.14 mm per decade, with a R^2 value of 0.0064. Change rates of PF and MWL were 45 m^3/s and 0.067 m per decade, with an R^2 value of 0.0046 and 0.0062, respectively. LF showed a slight decrease with a change rate of -4.8 m^3/s per decade. There are no statistical significant changes in precipitation, LF, PF and MWL during the period of 1954–2006 at the 95% confidence level (Table 2). Runoff and sediment load showed an upward trend with a change rate of 11.4 mm and 4 t per decade, respectively and the upward trend is significant at the 95% confidence level (Table 2). Fluctuations of precipitation and runoff occurred around 1979. Overall, both precipitation and runoff in the Jiuzhou station decreased during 1954–1979, then slightly increased, and finally decreased sharply again in 2006. The change curve of the runoff was similar to that of the sediment load since 1970, indicating that the sediment load had better correlation with annual runoff. Figure 4 helps to better find the correlation of sediment load change with hydrological elements and analyze the response of sediment load to the hydrological changes.

Although several dams have been planned in the upstream of Jiuzhou Station, these dams are still in a feasibility study phase, and no dam has been completed. The MWL was measured in the natural river. The significant upward trend of sediment load, however, occurred along with no statistical significant change in MWL during the same period. It seems that apparent change in sediment load is not affecting MWL in the river channel, and there is a stable channel in the upstream part of the Lancang-Mekong River. Further studies are needed to account for such a phenomenon.

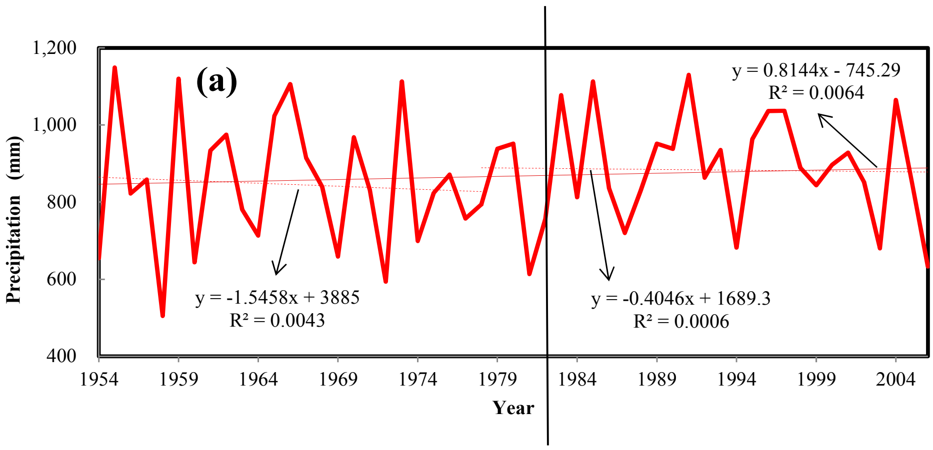
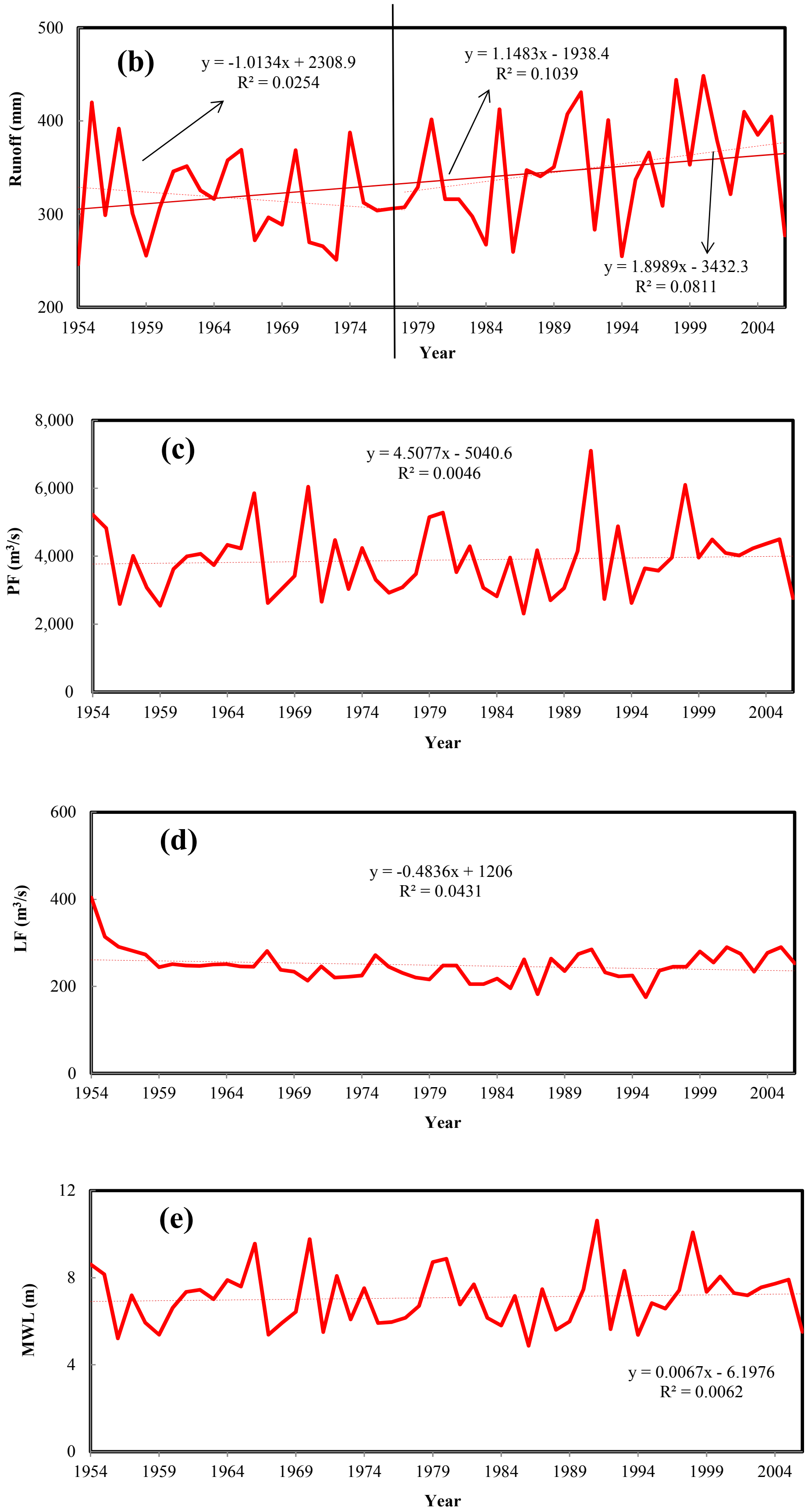


Figure 4. *Cont.*



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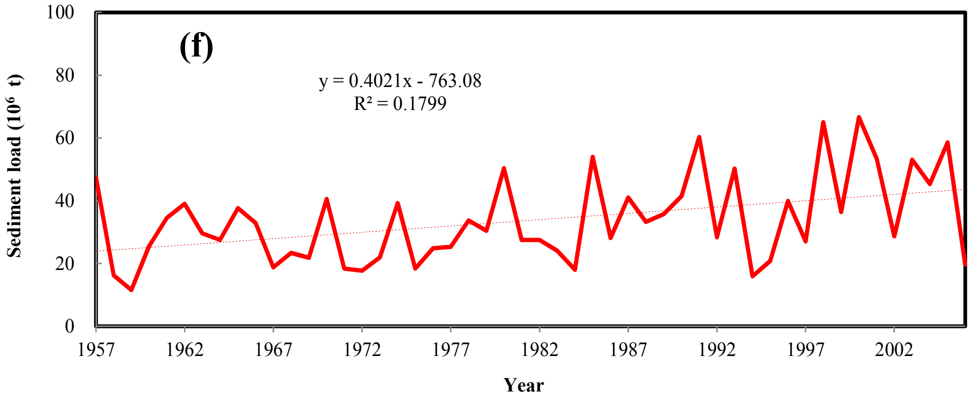

Figure 4. Time series of annual precipitation (**a**), runoff (**b**), PF (**c**), LF (**d**), MWL (**e**), and sediment load (**f**) during the period of 1954–2006 at Jiuzhou Station. Note: Time series of sediment load only cover the period of 1957–2006.

Table 2. Correlation coefficients of observed hydrological elements and sediment load at Jiuzhou Station from 1957 to 2006.

Precipitation	Runoff	PF	LF	MWL	Sediment Load
0.08	0.32 *	0.07	−0.21	0.08	0.42 *

* Significance at the 95% confidence level.

4.3. Relationships of Sediment Load between Runoff, MWL, PF, and LF

The relationships of sediment load between annual runoff, PF, LF, and MWL were also investigated (Figures 5 and 6). Figure 5a,b shows the relationships of sediment load with runoff before and after the 1980s. Runoff positively correlated with sediment load during the two periods (1957–1979 was the first period, and 1980–2006 was the second period), the correlation coefficient between runoff and sediment load during the first period (Figure 5a) was generally smaller than those during the second period (Figure 5b), accounting for the similar change curves of runoff and sediment load especially after 1979 (Figure 4). The sediment load had significant positive correlations with runoff in the two periods at the 99% confidence level (Table 3), in particular larger significant positive correlation in the second period, indicating the greater effect of runoff change on sediment load in the upstream part of the Lancang-Mekong River. The sediment load correspondingly increased when runoff showed an upward trend. The result demonstrates the conclusion that a majority part of the sediment load can be explained by the maximum discharge and the runoff [10]. Given the better correlations of runoff and PF with sediment load, the operation of dams could play an important role in the sediment load change through (extreme) runoff regulation in the upstream part of the Lancang-Mekong River. Figure 6 indicates that, at the 99% confidence level, the annual LF had nonsignificant negative correlation with sediment load over the past 50 years (Figure 6b), and the correlation was weaker than that of PF (Figure 6a), MWL (Figure 6c), and annual runoff.

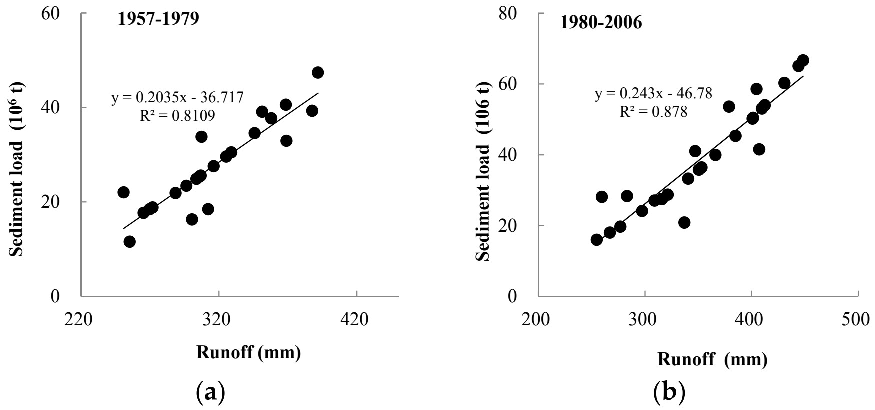

Figure 5. Scatter plots between annual runoff and sediment load during the periods of 1957–1979 and 1980–2006 at Jiuzhou Station.

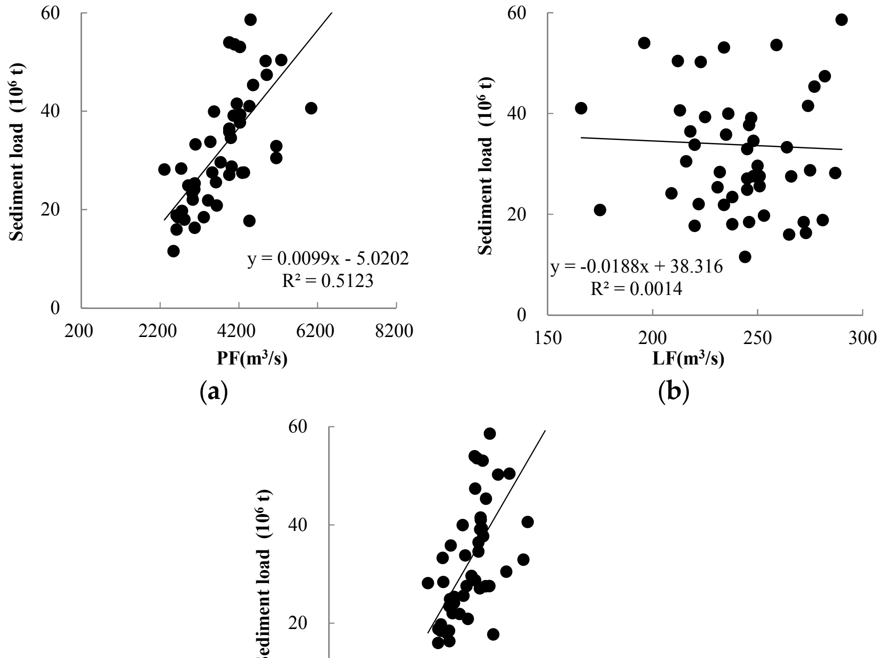

Figure 6. Scatter plots between PF, LF, MWL, and annual sediment load during the periods of 1957–2006 at Jiuzhou Station.

Table 3. Correlation coefficients between observed hydrological elements and sediment load at Jiuzhou Station from 1957 to 2006.

Period		Runoff	PF	LF	MWL
1957–2006	1957–1979	0.91 *	0.716 *	−0.04	0.67 *
	1957–2006	0.94 *			

* Significance at the 99% confidence level.

Overall, the increasing trend in sediment load agrees with prior search [41–45], and based on the significant increasing trend of runoff and its significant positive correlation with sediment load, it can be inferred that the increase of sediment load could be mainly attributed to the increase of runoff caused by slight increase of precipitation and land cover change (i.e., from arable and forested land to construction land since the mid-1980s in Yunnan [22]) in the upstream part of the Lancang-Mekong River since 1980.

4.4. Quantitative Importance of Annual Precipitation, Runoff, FP, LF, and MWL to the Sediment Load Change

Table 4 shows the RF variable importance of annual precipitation, runoff, FP, LF, and MWL to the sediment load change in the upstream part of the Lancang-Mekong River. Among the five aforementioned hydrological elements, runoff had the largest VI with an IncMSE of 8.62%, followed by PF and MWL with an IncMSE of 7.54% and 6.99%, respectively. LF as well as annual precipitation had a small VI with an IncMSE of less than 2%. The VI of each aforementioned hydrological element corresponded to its correlation with the sediment load change (Figure 6 and Table 4), which further demonstrated that annual runoff, PF, and MWL were the three main driving factors that caused the sediment load change in the upstream part of the Lancang-Mekong River over the past 50 years.

Table 4. VI of precipitation, runoff, PF, LF, and MWL to the sediment load change.

Variable	IncMSE (%)	Ranking
Precipitation	1.87	4
PF	7.54	2
LF	1.26	5
Runoff	8.62	1
MWL	6.99	3

In the current study, we found that both runoff and sediment load showed an upward trend at the 95% confidence level in the upstream part of the Lancang-Mekong River over the past 50 years, and runoff had the largest variable importance to the sediment load change, followed by PF, MWL, precipitation, and LF. These findings are similar to the findings of other parts of the world. For instance, in the Magdalena drainage, Colombia, the observed sediment yield was mainly influenced by mean annual runoff and runoff explained 51% of the variance in sediment yield [8]. In a Mediterranean mountainous catchment in the NE Iberian Peninsula, suspended sediment concentrations and sediment load were largely correlated with flood magnitude and the amount of direct runoff, respectively [11]. However, similar research in different parts of the world could also give rise to different findings. For example, in James Ross Island, Antarctica, suspended sediment concentrations were very high due to aeolian supply and the high erodibility of local rocks [46]. In the Sacramento River Basin, California, the observed historical sediment decline was supported by a significantly decreasing trend of sediment concentrations and seasonality and decline of snowpack [47]. In the Jiulong River in Southeast China, rainstorm events had a pronounced influence on the changes of suspended sediment concentration in the rivers over short timescales [48]. In the Loess Plateau, China, the sediment yield and runoff exhibited decreasing trends principally related to human activity [49]. In a small high Arctic watershed in Canada, the antecedent moisture conditions and permafrost active layer development were the two important factors affecting sediment transport response to precipitation events [14]. In the Chhota Shigri glacier, Western Himalaya, India, changes of suspended sediment concentration were directly associated with diurnal variations in meltwater runoff with a strong correlation [6]. Given this, it can be concluded that, the changing process of sediment load and the response to hydrological elements are complex and vary in different spatiotemporal scales, according to the climate condition, topography, and intensity of human activity of the river basin.

5. Conclusions

To investigate the response of sediment load to the changes of hydrological elements in the upstream part of the Lancang-Mekong River, a sediment rating curve for the Jiuzhou Station was developed based on the data collected from 1957 to 2006, and trends in annual runoff, PF, LF, MWL, and sediment load were studied by using the linear regression analysis method. The Random Forest algorithm was adopted to quantitatively quantify the importance of each aforementioned hydrological element to the sediment load change. The following conclusions were drawn from this study:

(1) During the period 1957–2006, PF, LF, and MWL had no significant change; both runoff and sediment load showed an upward trend at the 95% confidence level in the upstream part of the Lancang-Mekong River.
(2) Runoff, PF, and MWL had positive correlation coefficients with sediment load. Sediment load had stronger correlation with runoff than with other hydrological elements, especially after 1980, at the 99% confidence level.
(3) Runoff had the largest VI to the sediment load change, followed by PF, MWL, and LF in the upstream part of the Lancang-Mekong River over the past 50 years. The largest variable importance of runoff demonstrated the better correlation of runoff with sediment load compared to other hydrological elements.

It can be obtained that reasonable regulation of runoff, particularly by the planned dams, and runoff forecasting are essential to manage the sediment load in a sustainable way in the upstream part of the Lancang-Mekong River, given that the sediment load change responded more to runoff and extraordinary flood events. Climate-induced suspended sediment discharge alteration and its implication in the upstream part of the Lancang-Mekong River can be studied further.

Author Contributions: Y.H. designed this study and wrote the manuscript; Z.G. and C.S. analyzed the data. D.C., K.L., and X.B. collected the data and provided suggestions to the manuscript; X.C. guided the study and provided the suggestions and improvements to the manuscript. All authors read and approved the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

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