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Article

The Lag Effect of Riverine Flow Discharge and Sediment Load Response to Antecedent Rainfall with Different Cumulative Durations in Red Hilly Area in China

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Abstract: Rainfall is the main driver of soil erosion. With the daily rainfall, riverine flow discharge, and sediment load in the upper Lianjiang River watershed from 1990 to 2020, extreme rainfall events were defined by the 95th percentile method and minimum event interval time (MIT), change trends and mutations of yearly rainfall, riverine flow discharge and sediment load were identified using the Mann-Kendall test, then the optimum lag response time and antecedent rainfall were investigated with the multiple linear regression. The results showed that (1) the sediment changed significantly and abruptly in 1995 due to the expansion of the garden land. (2) Compared with ordinary rainfall, extreme rainfall events explained more variations of riverine flow and sediment with a higher degree, and had a more significant effect on the lag time of runoff and sediment. (3) Garden land expansion in extreme rainfall scenarios resulted in longer lag times for runoff and sediment, and decreased demand for antecedent rainfall with more pre-event time. Therefore, taking the rainfall event as a breakthrough, analyzing the antecedent rainfall and the lag response of riverine flow discharge and sediment load is conducive to revealing the response mechanism of riverine flow discharge and sediment load and improving the simulation accuracy of riverine flow and sediment under extreme rainfall condition, thus help for the soil erosion control under extreme rainfall.

Keywords: antecedent rainfall; lag time; rainfall event; extreme rainfall; garden land expansion; red hilly area in China

1. Introduction

The riverine flow-sediment relationship is an extremely complex hydrological process, and the impacts of climate change and human activities on riverine flow-sediment changes are hot topics that have been discussed[1,2]. Numerous studies have shown that climate change has altered riverine flow discharge and sediment load, which has been exacerbated by intense human activities. Riverine flow discharge and sediment load depend on a series of flow and sediment generation and transportation related processions, which spatial and temporal variations are easily affected by the temporal and spatial distribution of rainfall, evaporation, infiltration, runoff generation, and soil erosion[3]. Clarifying the study period is the key to discussing flow-sediment changes [3–7]. There is a lag effect in the influence of rainfall events on runoff and sediment, and the antecedent rainfall also affects the lag effect[8]. Antecedent rainfall and rainfall events both play an important role in the variation of flow discharge and sediment load.

In the red hilly area of China, the annual rainfall is high, ranging from 1.9 to 2.8 times the national average level, and is disproportionally distributed throughout the year[9]. This region is particularly vulnerable to extreme rainfall from April to September, making it one of China's most affected areas by water erosion[10]. Riverine sediment load is primarily triggered by rainfall[11,12]. The impact of

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extreme rainfall on riverine sediment load is particularly severe. Extreme rainfall strikes the soil and increases riverine sediment load[13]. Extreme rainfall events demonstrate more comprehensively the effects of rainfall on riverine runoff discharge and sediment load, providing valuable insights into this relationship.

Antecedent rainfall increases soil moisture and reduces soil infiltration when the next rainfall occurs. The significance of antecedent rainfall in sediment load processes cannot be understated. Studies have confirmed that the runoff coefficient can double when the soil is moistened by antecedent rainfall compared to dry soil conditions. Also, moist soils accelerate the occurrence of runoff during rainfall[14,15]. Antecedent rainfall increases soil moisture, improves runoff conversion efficiency, and accelerates riverine runoff discharge[13,16]. It also enhances water erosion and increases riverine sediment load. The amount of riverine sediment load after rainfall is influenced by moist soil before the event[17]. Another study showed that nearly 70% of the runoff was related to the antecedent soil water content[18]. Antecedent soil moisture correlates more strongly with the riverine flow. Antecedent soil moisture and rainfall are the important factors influencing riverine flow discharge[14,19], and the combination of antecedent rainfall and intra-event rainfall is vital to generating riverine flow discharge and sediment load[14,20]. Larger floods caused by extreme rainfall respond more strongly to antecedent rainfall[21,22]. Riverine sediment is also affected by antecedent rainfall that accumulates in the soil[23], which is an easily overlooked effect[24]. Rainfall intensity and antecedent rainfall are also important contributors to changes in riverine flow discharge and riverine sediment[2,25,26], and their specific roles can differ depending on the region[8,22,27,28]. Only sufficiently accumulated antecedent rainfall in the soil can trigger massive riverine sediment in response to extreme rainfall[29,30]. All the above studies show that the effect of antecedent rainfall on riverine flow discharge and sediment load in the watershed is very significant.

Rainfall is a major driver of soil erosion and the primary inducing factor of riverine flow discharge and sediment load. Therefore, this study attempts to investigate the lag response effect of the riverine flow discharge and sediment load to antecedent rainfall and explore the influencing factors of the lag response effect, which will help to reveal the response mechanism of riverine flow discharge and sediment load and improve the simulation accuracy of riverine flow and sediment under extreme rainfall condition.

2. Materials and methods

2.1. Study area

Lianjiang River Watershed (115°11′53″~115°11′53″E, 25°02′52″~25°21′10″N) with a total watershed area of 2339km^2, located in the southern red soil area in China. As seen in Figure 1, the Lianjiang River is a first-class tributary of the upper Ganjiang River. Ganjiang River is the largest inlet river of Poyang Lake, the largest freshwater lake in China.

The average annual temperature is 18.7°C, the annual runoff is 1.92 billion m^3, and the annual suspended mass sediment transport is 259,000 t[9]. There is a hydrological station of Yangxinjiang in the upper reaches of the Lianjiang River, controlling a watershed area of 568 km^2, which is defined as the upper watershed of the Lianjiang River in this study. Anyuan County, where the upper Lianjiang River watershed is located, vigorously promoted citrus cultivation in the early 20th century for policy reasons, leading to dramatic changes in land use structure[9].

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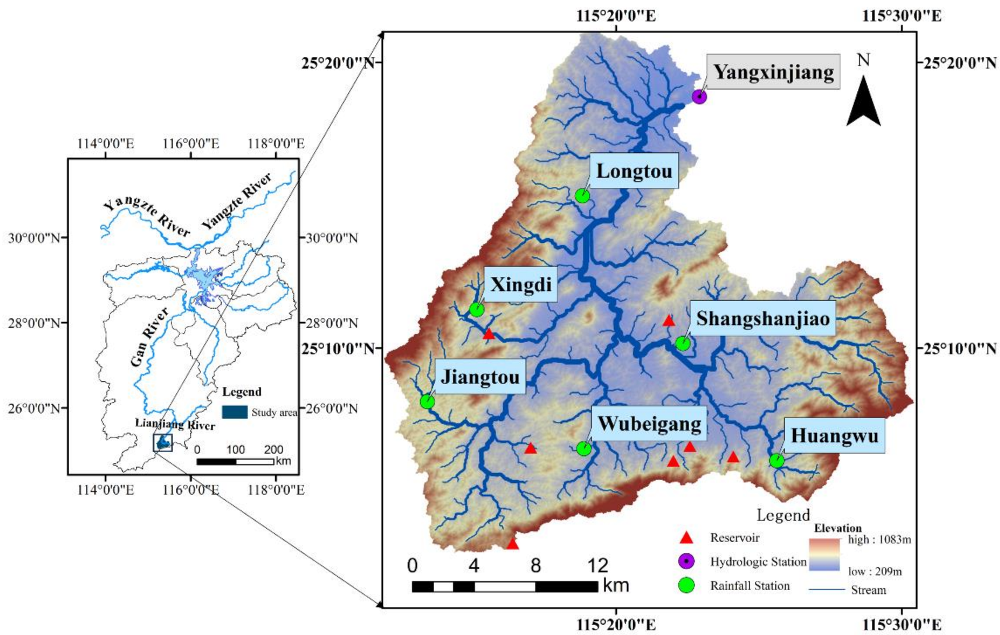

Figure 1. Location of the study area in Poyang Lake Watershed and the distributions of rainfall and hydrologic stations.

2.2. Data collection

The hydrological data were obtained from the Jiangxi Provincial Hydrological Monitoring Center, which is the official hydrological monitoring institution with the standard specifications for hydrological monitoring to acquire detailed and reliable hydrological data. This paper collected daily rainfall data from six rainfall stations (Huangya, Shangshanjiao, Yabigang, Xingdi, Jiangtou, and Longtou) and one hydrological station (Yangxinjiang hydrological station) in the upper watershed of the Lianjiang River from 1990 to 2020, as well as daily runoff and sediment data from the Yangxinjiang hydrological station for the same period.

The land use data were obtained from the geographic monitoring cloud platform (http://www.dsac.cn/) with a spatial resolution of 30m during 1990-2020, with four periods of 1990, 2000, 2010, and 2020[31], which is one of the most authoritative land use data in China. Land use types are divided into 6 primary categories and 25 secondary categories, of which the average classification accuracy of crop land and urban-rural, industrial, mining, and residential land reaches more than 85%, and the average classification accuracy of other land use types is more than 75%[31]. In this data, the other wooded land refers to young afforested land, traces, nurseries, and various types of gardens (orchards, mulberry gardens, tea gardens, hot crop gardens, etc.). Referring to the corresponding garden area of Anyuan County in the statistical yearbook of Ganzhou City from 1992 to 2020[32], the other wood land could be identified as garden land in the study area.

2.3. Definition of extreme rainfall events

The rainfall data of the Lianjiang River watershed is based on rainfall data from seven stations. The average daily rainfall is calculated by the Thiessen polygon as the following formula.

$$R = \sum_{i=1}^{n} R_i \frac{s_i}{S} \tag{3-1}$$

where R_i is the amount of rainfall greater than 1 mm at each rainfall station (mm), s_i is the control area of each rainfall station (km^2), S is the total area of the watershed (km^2), n is the number of rainfall stations, and here n=7 is taken. In this paper, the daily rainfall is selected to be greater than 1 mm,

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and the 95th percentile value was used as the threshold value[33]. The threshold for extreme rainfall in the upper reaches of the Lianjiang River watershed was calculated based on the average daily rainfall and is determined to be 41.71 mm.

2.4. Mann-Kendall test

The Mann-Kendall method, or M-K Test, is a non-parametric diagnostic technique that can be applied to determine whether there is an abrupt change in a time series data, and if so, when it occurs [34]. In this study, the M-K test was applied to the yearly rainfall, riverine flow discharge, and sediment load data to detect whether there was an abrupt change and which year the abrupt change happened.

2.5. Pre-processing of hydrological data

When calculating rainfall events, only two rainfall events separated by 7 days are selected in this study, to avoid overlapping rainfall events affecting the single rainfall function. During the period 1990-2020, there were 150 extreme rainfall events and 740 ordinary rainfall events.

2.6. Multiple regression analysis

Multiple linear regression models are an intuitive and efficient way to analyze complex problems[35]. In this study, we used the rainfall of the rainfall event as the fixed independent variable and the riverine flow discharge or sediment load within the event as the dependent variable. We added antecedent rainfall at different accumulation times as an independent variable and riverine flow discharge or sediment load at different time durations as a dependent variable. The multiple linear regressions were fitted sequentially with the combination of every AP and RA or SA list in Tab.1. The optimal model was selected based on the highest R^2, which implied the highest degree of explanation.

Table 1. Indicator labels and content.

Labels	context
AP1	Rainfall on the last day before an extreme rainfall event
AP2	Cumulative rainfall of the last 2 days before an extreme rainfall event
AP3	Cumulative rainfall of the last 3 days before an extreme rainfall event
AP5	Cumulative rainfall of the last 5 days before an extreme rainfall event
AP7	Cumulative rainfall of the last 7 days before an extreme rainfall event
RA1	Flow discharge of the next day after an extreme rainfall event
RA2	Cumulative flow discharge of the next 2 days after an extreme rainfall event
RA3	Cumulative flow discharge of the next 3 days after an extreme rainfall event
RA5	Cumulative flow discharge of the next 5 days after an extreme rainfall event
RA7	Cumulative flow discharge of the next 7 days after an extreme rainfall event
SA1	Sediment load of the next day after an extreme rainfall event
SA2	Cumulative sediment load of the next 2 days after an extreme rainfall event
SA3	Cumulative sediment load of the next 3 days after an extreme rainfall event
SA5	Cumulative sediment load of the next 5 days after an extreme rainfall event
SA7	Cumulative sediment load of the next 7 days after an extreme rainfall event

3. Results

3.1. Change characteristics of rainfall, riverine flow discharge, sediment load, and garden land

From 1990-2020, there were a total of 205 days with daily rainfall exceeding the given threshold and 3,888 days with daily rainfall between 1mm and the threshold. The yearly rainfall varied between 1080.9-2174 mm (Figure 2.a), the yearly riverine flow discharge ranged from 172.39-1017.07×10^6 m^3 (Figure 2.c), and the yearly riverine sediment load ranged from 0.57-64.30×10^4 t (Figure 2.e) from 1990 to 2020. The M-K test showed that rainfall (Figure 2.b) and riverine flow discharge (Figure 2.d) did not undergo a significant mutation (P>0.05) from 1990 to 2020. Only riverine sediment load undergoes a significant mutation, and the year of mutation is 1995 (P=0.041) (Figure 2.f). Therefore, the study period could be split into two periods with the abrupt year, thus 1990-1995 is period 1(P1) and 1996-2020 is period 2(P2). Subsequently, the effects of rainfall events on riverine runoff discharge and sediment load were dissected under the above two different periods.

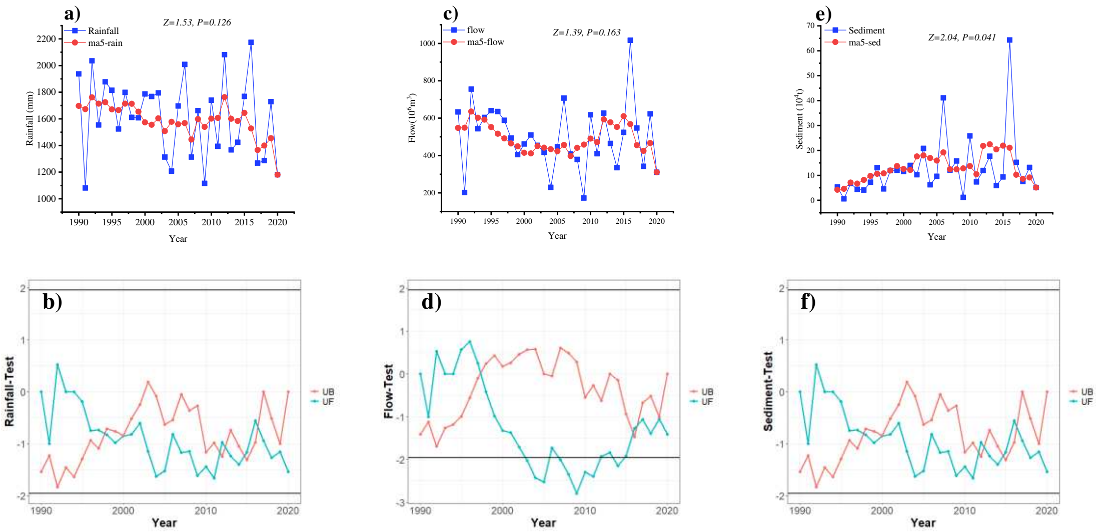

Figure 2. Annual variations, and Mann-Kendall test in rainfall (a and b), flow discharge (c and d), and sediment load (e and f).

The garden area in Anyuan County was generally increasing from 1992 to 2020, reaching a peak of 192.59 km^2 in 2014. (Figure 3). In terms of spatial expansion, newly developed orchards were relatively concentrated distribution, and located mainly near the main stream and main tributaries of the Lianjiang River (Figure 7).

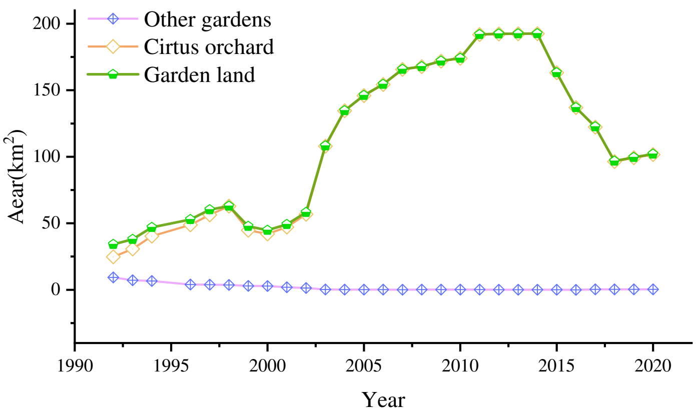

Figure 3. The area of garden land in Anyuan country, from 1992 to 2020.

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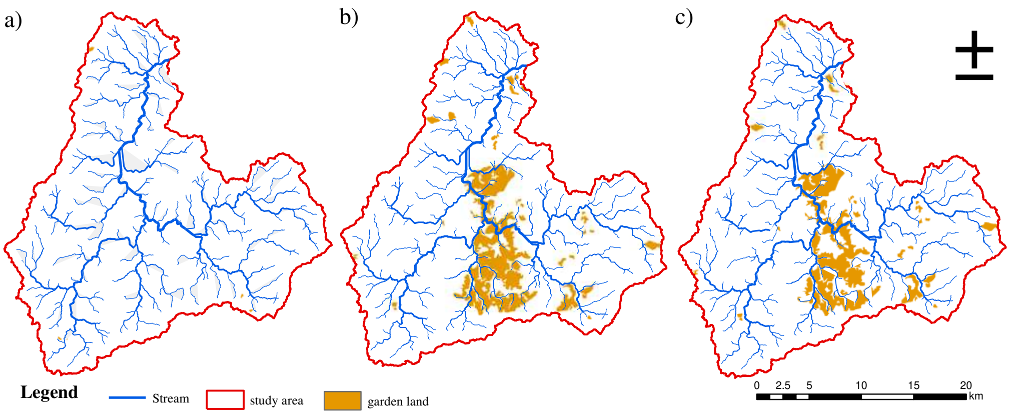

Figure 7. Spatial distribution of garden land in the upper Lianjiang River watershed (a: 1990, b: 2010, c: 2020).

3.2. Statistical characteristics of rainfall, runoff, and sediment in different periods

Compared to the P1 period, the extreme, ordinary, and total rainfall and their corresponding riverine flow discharge decreased in the P2 period, while their corresponding riverine sediment load increased (Figure 5). Overall, extreme rainfall was less than ordinary rainfall, as was the frequency of extreme rainfall events. Taking the difference in rainfall amounts into account, extreme rainfall had a greater capacity to produce sediment than ordinary rainfall (Figure 5). The two periods meant for the frequency of extreme and ordinary rainfall events varied little, with a slightly different range of variability (Figure 6).

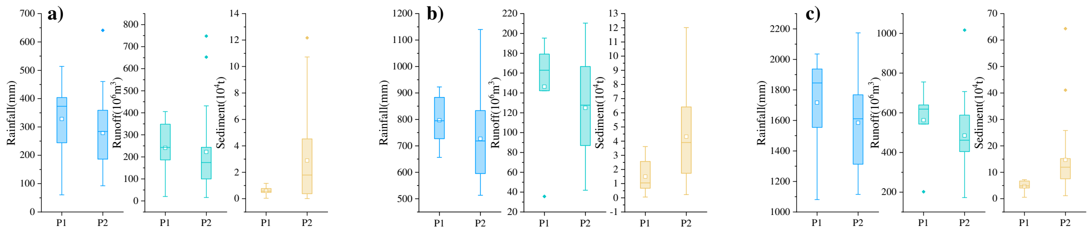

Figure 5. Distribution characteristics of extreme rainfall (a), ordinary rainfall (b), total rainfall (c), and their corresponding riverine flow discharge and sediment load for different periods. Solid lines and square in this figure represent the median and mean, respectively. The box boundaries represent the 75% and 25% quartiles, the whisker caps represent the 90% and 10% quartiles, and the circles represent the 95% and 5% quartiles.

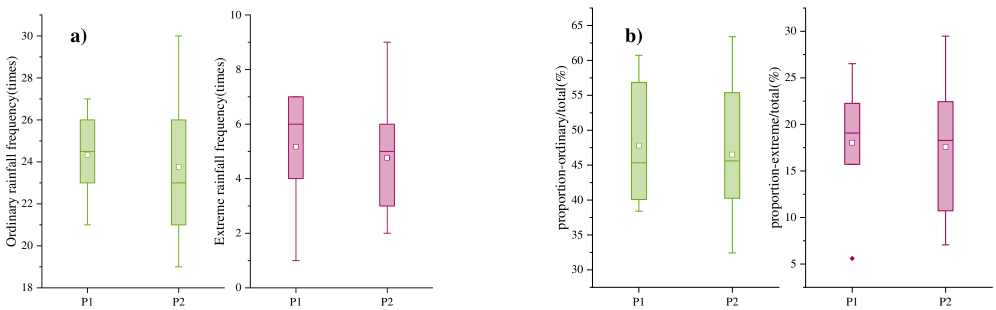

Figure 6. The frequency(a) and proportion(b) distribution of ordinary and extreme rainfall in different periods. Solid lines and square in this figure represent the median and mean, respectively. The box boundaries represent the 75% and 25% quartiles, the whisker caps represent the 90% and 10% quartiles, and the circles represent the 95% and 5% quartiles.

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3.3. Impact of antecedent rainfall on runoff

From the period of P1 to P2, the optimal influence factor of the preceding rainfall on runoff in the extreme rainfall scenario changed from AP5 to AP7. The affected riverine flow discharge was extended from RA1 to RA7 (Table 2), and the degree of explanation in the period of P2 declined from 0.729 to 0.470. In contrast, the optimal influencing factor of riverine flow discharge by the antecedent rainfall changed from AP7 to AP2 in the ordinary rainfall scenario, and the affected riverine flow discharge was RA1 in both periods (Table 2).

Table 2. Multiple regression modeling of antecedent rainfall and riverine flow discharge under extreme and ordinary rainfall scenarios for different periods.

Type	Periods	Antecedent rainfall	Flow discharge	R^2	*n*	*p-value*
Extreme rainfall	P1(1990-1995)	AP5	RA1	0.729	31	***
	P2(1996-2020)	AP7	RA7	0.470	119	***
Ordinary rainfall	P1(1990-1995)	AP7	RA1	0.461	146	***
	P2(1996-2020)	AP2	RA1	0.477	594	***

Note: R^2 represents the extent to which the model can explain the variation in the data ; "n" represents the total number of samples available in the dataset; "***" represents a high level of significance, indicating that the p < 0.001.

3.4. Impact of antecedent rainfall on sediment

The regression model was statistically significant (P<0.05) only in the extreme rainfall scenario (Table 3). During the P1 period, AP3 was the antecedent rainfall with the highest degree of explanation of riverine flow discharge, whereas the corresponding dependent variable was SA1. During the P2 period, AP7 and SA7 were the most highly explained independent and dependent variables, respectively. From P1 to P2, R^2 decreased from 0.554 to 0.245 for the extreme rainfall scenario (Table 3).

Table 3. Multiple regression modeling of antecedent rainfall and sediment under extreme and ordinary rainfall scenarios for different periods.

Type	Periods	Antecedent rainfall	Sediment	R^2	*n*	*p-value*
Extreme rainfall	P1(1990-1995)	AP3	SA1	0.554	31	***
	P2(1996-2020)	AP7	SA7	0.245	119	***
Ordinary rainfall	P1(1990-1995)	AP7	SA2	0.059	146	0.077
	P2(1996-2020)	AP7	SA7	0.011	594	0.816

Note: R^2 represents the extent to which the model can explain the variation in the data ; "n" represents the total number of samples available in the dataset; "***" represents a high level of significance, indicating that the p < 0.001.

4. Discussion

Previous researchers have broadly attributed changes in riverine flow discharge and sediment load to both climate change and human activities [6,36,37]. Rainfall changes in the upper Lianjiang River watershed were not significant, so it was inferred that the dramatic increase in sediment could be due to human activities. The expansion of the garden land in the study area is drastic, and no large or medium-sized reservoirs were built in the study area[9]. During the P2 period, extreme rainfall explained less of the riverine flow discharge (Table 2) and sediment load (Table 3), which may be related to the enhancement of human activities (orchard expansion). Conversion of orchards from forested land reduces surface vegetation cover and consequently runoff losses[38,39], which has a reduced scouring and transporting effect on soil particles.

Garden expansion increases riverine sediment load in the red hilly area in China[5], and the same phenomenon is observed in the provinces of Granada and Málaga[40]. During the P2 period, the degree of explanation (R^2) of rainfall events on riverine flow discharge decreased to 0.470 for the extreme rainfall scenario (Table 2). Most of the new gardens were found near the main stem of the river (Figure 7). The conversion of land to orchards significantly impacts riverine flow discharge and sediment load[40]. Newly Reclaimed orchards often have severe soil erosion, and increase riverine sediment load[1,11,15]. The presence of orchards near the main stem of the river reduces the distance over which runoff reaches the river, thereby increasing riverine flow discharge and sediment loads. Orchard development or clean-cultivated orchards increased riverine sediment load[41–44]. In orchards, more than 80 percent of rainfall is lost through runoff, which can be reduced by 86 percent with optimal tillage practices[18]. Management practices in orchards are vital to riverine flow discharge and sediment load[45]. The implementation of soil and water conservation measures in orchards is effective in reducing riverine sediment load[42,44]. Extreme rainfall events and orchard management practices are key factors influencing sediment yield in orchards[46].

The degree of explanation (R^2) for the response of riverine sediment load to antecedent rainfall was reduced to 0.245 (Table 3) during the P2 period. Soil and water conservation measures have played a crucial role in orchards[47]. With the fully functioning of soil and water conservation measures (e.g., horizontal terraces, anti-slope terraces, grass strip et.al) after orchard maturity, water infiltration, and water retention capacity was effectively increased, and the time for runoff to reach the river was prolonged [45]. In addition, restored vegetation can effectively obstruct runoff from saturated soils[48]and reduce sediment load[42,46]. Vegetation restoration also lengthens the time of runoff from the slope to the flow into the river. Those all explain the insignificant response of riverine sediment load to rainfall in the ordinary rainfall scenario during P2.

Extreme rainfall is a strong driver of riverine flow discharge and sediment load changes[2,9]. In other words, extreme rainfall is an important environmental factor for the lag time of antecedent rainfall on riverine flow discharge and sediment. Extreme rainfall produces fast-flowing runoff that is less consumptive than ordinary rainfall. The lag time of riverine flow discharge depends on the soil moisture conditions before the event[49]. Rainfall intensity severely affects flow discharge lag time, and high intensity and long-duration rainfall shortens the response time of river runoff. [50]. Ordinary rainfall, on the other hand, requires the soil to reach the moist threshold for runoff to occur[14]. Rainfall and rainfall intensity are also important factors in the lag time of riverine flow discharge[51,52].

During the P2 period, the lag time of the riverine flow discharge response to the rainfall was shortened from AP7 to AP2, in the ordinary rainfall scenario (Table 2). Garden land reclamation removed vegetation from the surface. The consumption of runoff is reduced, and the demand for antecedent rainfall is reduced. Under the extreme rainfall scenario, the lag time for both riverine flow discharge and sediment during P2 is 7 days, and the duration of the antecedent rainfall corresponding to the riverine flow discharge and sediment is also 7 days (Table 2 and Table 3). Changes in riverine flow discharge are closely related to antecedent rainfall and land use[38]. The conversion process destroys the original ground cover[53], reducing evapotranspiration and moisture absorption from antecedent rainfall [54]. Soil moist conditions can significantly increase riverine sediment concentration[55]. The lag time for riverine flow discharge is one day after the rainfall event for extreme rainfall in period P1 and for ordinary rainfall in both periods, while the lag time for riverine flow discharge is seven days after the rainfall event for extreme rainfall in period P2. On the one hand, ordinary rainfall events bring less moisture and even less runoff into the river, and the lag time of riverine flow discharge changes weakly. On the other hand, riverine flow discharge from extreme rainfall events is more responsive to orchard expansion, and a longer lag time for riverine flow discharge means more riverine flow discharge is generated.

5. Conclusions

In this paper, based on the rainfall, flow discharge, and sediment load in the upper Lianjiang River watershed in the red soil area of southern China during 1990-2020, extreme rainfall events were defined, the mutation points of flow discharge and sediment load data series was determined to separate the study period into two different periods, and the respond lag time of riverine flow discharge and sediment load to antecedent rainfall with different preceding days were investigated for two different periods and two types of rainfall. The results show that:

(1) from 1990 to 2020, the sediment load had a significant abrupt change in 1995, while there was no abrupt change in rainfall and flow discharge. The garden area increased drastically from 1995 to 2020, and it was concentrated near the main stem of the river, and the change in riverine sediment load was related to the increase in the garden area.

(2) Compared with ordinary rainfall events, extreme rainfall events explained riverine flow discharge and sediment load with a higher degree, thus having a more significant effect on the lag time of riverine flow discharge and sediment.

(3) Expansion of the garden land resulted in longer lag times for riverine flow discharge and sediment load, and its lag time in response to the preceding rainfall was extended. Garden development and maturity enhanced the construction of runoff and sediment and reduced soil erosion.

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Conflicts of Interest: All authors declare no conflict of interest.

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