



Effect of Check Dam on Sediment Load Under Vegetation Restoration in the Hekou-Longmen Region of the Yellow River

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With years of vegetation restoration and check dam construction on the Loess Plateau, the sediment load of the middle reaches of the Yellow River have decreased sharply; however, the effects of check dam on this decrease of sediment load with such extensive vegetation restoration remains unclear. In order to further clarify the effects of check dam on sediment load reduction under vegetation restoration, we calculated vegetation coverage and check dam index based on multi-source remote sensing data, and calculated sediment reduction rate caused by human activities by Mann-Kendall statistical test and double cumulative curve, then established regression equations incorporating the check dam index and the sediment reduction rate using data from different geomorphic regions with different vegetation coverages. The results showed that sediment load in the Hekou-Longmen region and its 17 tributaries decreased significantly every year, and the change in sediment load could be divided into 3 typical periods: the base period (P1), the period mainly impacted by check dam construction (P2) and the period with comprehensive impact of check dam construction and vegetation restoration (P3). Compared with sediment load of the tributaries during P1, the sediment load decreased by 60.96% during P2 and by 91.76% during P3. Compared with the contribution of human activities to the reduction in sediment load in P2, the contribution of human activities in P3 increased significantly, while that of precipitation decreased slightly. The sediment reduction effect of check dams is greater in basins with low vegetation coverage than in basins with high vegetation coverage. There are differences in sediment reduction effect of vegetation restorations in different geomorphic regions, and the effect of vegetation restoration alone have certain upper limits. Such as, the upper limit of sediment reduction rate of vegetation restoration for rivers flowing through the sandstorm region is 47.86%. Hence, only combined the construction of check dam with vegetation restoration can it achieve more significant sediment reduction benefit and control soil erosion more effectively.

Keywords: sediment load change, vegetation restoration, check dam, loess plateau, middle reaches of the yellow river

INTRODUCTION

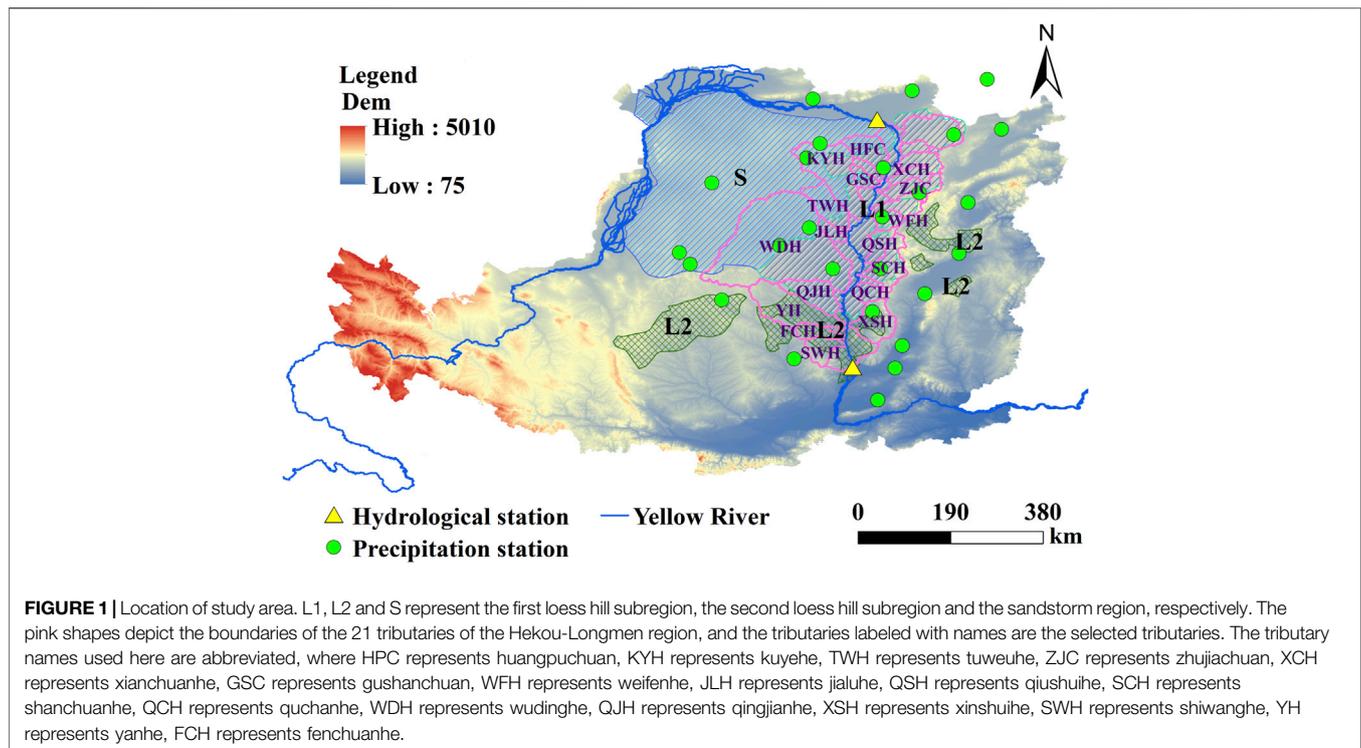
Soil erosion is a geomorphologic land degradation process that may cause environmental and property damage. Erosion not only lowers on-site soil quality but also causes significant off-site sediment-related problems (Munodawafa, 2007; Rickson, 2014; Poesen, 2018). The Loess Plateau in China, covering a 650,000-km² area in the middle and upper streams of the Yellow River basin, experiences the most intense soil erosion in the world (Pal et al., 2018; Jia et al., 2022). The Hekou-Longmen region on the Loess Plateau is one of the main sources of rainstorms and floods in the middle reaches of the Yellow River. In addition, this region is the main source area of coarse sediment in the Yellow River: the interval coarse sediment amount of the region accounts for 73% of the Yellow River coarse sediment amount, while the area of the region accounts for 14.8% of the Yellow River basin (Xu, 2004).

To effectively control soil erosion and restore ecosystems, the Chinese government has implemented various soil and water conservation measures over the past several decades (Fu et al., 2011; Sun et al., 2014; Cheng et al., 2018), among which check dam construction and vegetation restoration are the most widely used measures to control water and soil erosion. The construction of check dams on the Loess Plateau started in the 1950s. Currently, there are 113,500 check dams with heights over 5 m that have been built, and 163,000 check dams are planned to be completed by 2020 (Xiang-zhou et al., 2004; Abbasi et al., 2019). The Chinese government has implemented the Conversion of Cropland to Forest and Grassland Project in the Loess Plateau since 1999, and the area of forest and grassland converted from cultivated land reached 16,000 km²; this conversion has significantly changed the land-use type and improved the vegetation coverage of the region (Xiao, 2014; Feng et al., 2016). Check dam construction and vegetation restoration on the Loess Plateau have played important roles in controlling soil erosion and reducing river sediment load (Yang et al., 2008; Zhao et al., 2014; Chen et al., 2016).

Check dams are constructed in channels to trap upstream sediment (Boix-Fayos et al., 2008). A small reservoir is usually formed behind a check dam, and the reservoir gradually fills with sediment (Castillo et al., 2007). The trapped sediment forms a wedge behind the check dam body, lowering the bed channel slope, controlling flooding, and stabilizing gullied hillslopes (Hevia et al., 2014; Mongil-Manso et al., 2016; Galicia et al., 2019). With the increase in trapped sediment, the sediment storage capacity of the check dam decreases gradually while the formed wedge can reinforce the lateral slope of the gully, and reduce the probability of lateral instability ensuing (Gao et al., 2014; Piton et al., 2017). Tang et al. (2020) showed that filled check dams were still able to reduce sediment yield by 4–52% under different deployment strategies. Vegetation restoration generally leads to a decrease in the generation of runoff and sediment detachment (Beguería et al., 2006). Zhang et al. (2014) showed that forest and grassland had different reduction effects on runoff and sediment. The soil and water conservation functions of forests are improved by vegetative cover and plant root systems, which increase interception and infiltration, and decrease runoff and soil erosion. Grasslands directly intercept sediment through surface vegetative canopies.

Because of climate change and large-scale soil and water conservation measures, the runoff and sediment discharge of the main stream of the Yellow River and most of its tributaries have decreased significantly in recent decades (Hu et al., 2019; Zhao et al., 2019; Zheng et al., 2019). Many studies have indicated that human activities have been the main reason for this decrease in sediment load in the Yellow River basin (Yao et al., 2016; Gao G. et al., 2017; Fu et al., 2017). Mu et al. (2012) showed that sediment reduction caused by human activities accounted for 81% of the sediment reduction in the Yellow River basin from 1979 to 2008. The research results of Li et al. (2019) showed that before the 1990s, the construction of check dams was the main cause of reduced river sediment load; since 1999, large-scale afforestation has played an increasingly important role in this reduction. In addition, the contributions of vegetation restoration and check dam construction to the reduction of river sediment load are different among different basins. Based on the result that the construction of check dams reduced runoff and sediment load by 12 and 11.7%, respectively, and vegetation restoration reduced runoff and sediment load by 20.7 and 53.2%, respectively, Shi et al. (2019) studied the Wudinghe Basin and concluded that the sediment reduction effect of vegetation restoration was much higher than that of check dams. However, while studying the Huangfuchuan Basin, Zhao et al. (2017) showed that in the absence of check dams, the change in land use caused by vegetation restoration reduced the sediment yield in the basin by 31.4%, and in the absence of land-use change, the construction of check dams reduced the sediment yield of the basin by 51.9%; thus, the sediment reduction effect of check dams was greater than that of vegetation restoration. Boix-Fayos et al. (2008) showed that check dam was a more effective sediment control measure than vegetation restoration, but check dam have only a short-lived influence on sediment trapping, while vegetation restoration has important sustained effects.

In general, although there have been many studies on the relative effects of vegetation restoration and check dam construction on sediment reduction, studies of different research areas may produce opposite conclusions; thus, many challenges remain in terms of quantifying these effects. The main aim of this study was to reveal the effect of check dams on sediment reduction under the condition of vegetation restoration by analyzing the relationship between the sediment reduction rate caused by human activities and vegetation restoration and check dam construction. The normalized Difference Vegetation Index (NDVI) of the catchment and the location and the control area of check dams can be obtained by remote sensing images. Therefore, multi-source remote sensing data provide a data basis for analyzing the impact of vegetation restoration and check dam construction on watershed runoff and sediment load change. The specific objectives were to 1) study the variation trend of sediment load in the main stream of the Yellow River and its 17 tributaries and subsequently quantify the contribution of human activities to sediment reduction and 2) analyze the relationship between the sediment reduction rate caused by human activities and vegetation restoration and check dam construction in 17 tributaries of the middle reaches of the Yellow River, and reveal the sediment reduction effect of check dams under different vegetation coverages.



MATERIALS AND METHODS

Study Area

The Hekou-Longmen region is located in the upper part of the middle reaches of the Yellow River (between $108^{\circ}02'–112^{\circ}44'$ E, $35^{\circ}40'–40^{\circ}34'$ N), with a catchment area of $111,586 \text{ km}^2$. The length of the main stream in this region is 723 km, and this main stream has an average channel gradient of 0.84%. There are 21 large tributaries with catchment areas greater than $1,000 \text{ km}^2$, and 17 of these tributaries are studied in this paper (Figure 1). The region has an arid and semiarid climate, and the annual average precipitation is between 310 and 580 mm. The spatial precipitation distribution is extremely uneven and gradually decreases from southeast to northwest.

This area is in the middle of the Loess Plateau, covered with a deep loess layer. The average gully density is $5–6 \text{ km/km}^2$, and the gully area accounts for 40–50% of the total area. The geomorphologic types in this area are divided into the first loess hill subregion, the second loess hill subregion and the sandstorm region, accounting for 62, 24 and 14% of the basin area, respectively. The Hekou-Longmen region is the area experiencing the most serious soil erosion in China. In an area of $71,600 \text{ km}^2$ in this region, the erosion modulus is above $5,000 \text{ t}/(\text{km}^2\cdot\text{a})$, accounting for 64.2% of the total area. The area in which the erosion modulus is between $15,000 \text{ t}$ and $20,000 \text{ t}/(\text{km}^2\cdot\text{a})$ is $44,000 \text{ km}^2$, accounting for 39.4% of the total area; furthermore, the area where the erosion modulus is higher than $20,000 \text{ t}/(\text{km}^2\cdot\text{a})$ is $12,000 \text{ km}^2$, accounting for 10.8% of the total area (Li et al., 2014). To curb serious soil erosion, large-scale ecological

construction measures have been implemented. Through measures such as returning farmland to forests and closing forests, the vegetation coverage of this region has significantly improved (Figure 2A). Additionally, 3,786 key check dams had been built by the end of 2011 (Figure 2B). After the treatment, the intensity of soil erosion in this area showed a downward trend, and the amount of sediment load decreased sharply (Gao et al., 2017b).

Data Sources

Considering the continuity and integrity of the data, annual precipitation data from 1957 to 2015 from 26 national meteorological stations were selected, and the meteorological stations are distributed uniformly in the Hekou-Longmen region (Figure 1). The annual precipitation data were provided by the China Meteorological Data Service Center (<http://data.cma.cn/>). The average rainfall in the catchment area was calculated by the inverse distance weighted method (IDW) (Khan et al., 2020). The runoff and sediment data for the main stream and 17 tributaries of the Yellow River from 1957 to 2015 were obtained from the Loess Plateau Science Data Center (<http://loess.geodata.cn/>), the Hydrological Yearbook of the People's Republic of China and the Yellow River Water Resources Bulletin. We used the differences in the measured runoff and sediment data between Hekou station and Longmen station to calculate the runoff and sediment data in the Hekou-Longmen region.

The vegetation data were calculated using the GIMMS NDVI dataset (period of 1982–2011, spatial resolution of 8 km). The

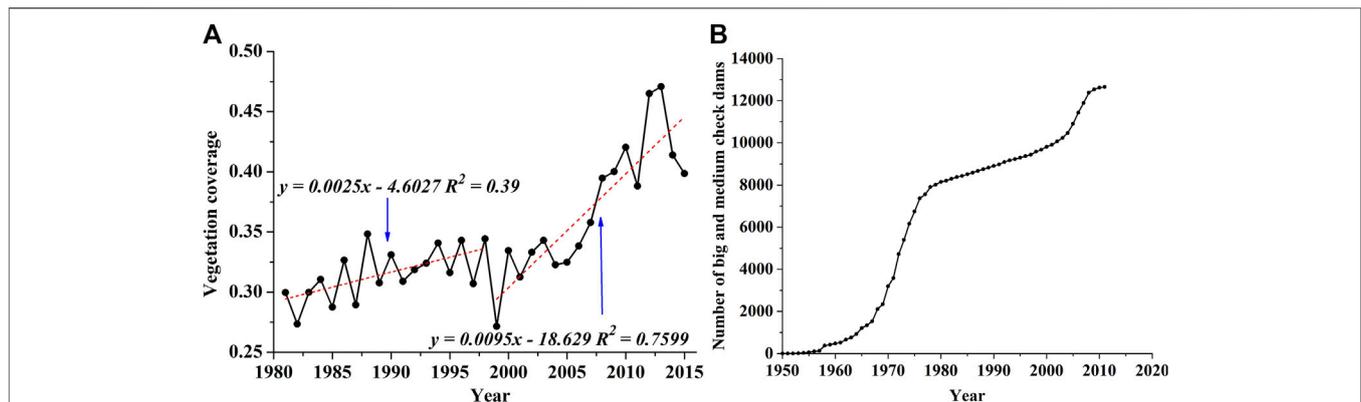


FIGURE 2 | Variations in (A) vegetation coverage and (B) number of check dams in the Hekou-Longmen region.

dimidiate pixel model was used to calculate the vegetation coverage (f) (Xu et al., 2018) as follows:

$$f = (NDVI - NDVI_{min}) / (NDVI_{max} - NDVI_{min}) \quad (1)$$

where $NDVI$ is the normalized difference vegetation index and $NDVI_{max}$ and $NDVI_{min}$ are the maximum and minimum $NDVI$ in the study area, respectively.

The key check dam data were obtained from the first national water conservancy census, which contains the construction year, control area, total storage capacity and siltation volume indexes at the end of 2011. The medium check dam data were obtained from the safety inspection of check dams conducted by the Ministry of Water Resources in 2008. Locations of all check dams were reviewed with Google Image, and control areas of some check dams were also reviewed.

METHODS

Trend Analysis

In this study, the variation trend of sediment load was analyzed by the Mann-Kendall statistical test. The Mann-Kendall statistical test is an effective nonparametric test method used to explore the variation trend in a time series (Mann, 1945; Vegelius, 1978), and has been widely applied in analyses of the variation trends of time series in the fields of hydrology and meteorology. (Pingale et al., 2014; Ribeiro et al., 2015; Han et al., 2020). The Mann-Kendall statistical test is robust for nonnormally distributed data, and a few outliers in the sample will not affect the results; thus, this test can reveal the variation trend of a time series well.

Change-point Analysis

The change-point analysis completed in this study was applied to determine the years in which abrupt changes in the sediment record may have occurred. The change points were determined using a robust nonparametric method at a significance level of 5% (Pettitt, 1979). The Pettitt's test is a non-parametric method widely applied to detect the abrupt changes of hydro-climatic variables (Li et al., 2020). This method detects a significant change

in the mean of a time series when the exact time of the change is unknown.

Effect Evaluation Analysis

The double mass curve is a widely used method to quantitatively evaluate the effects of precipitation change or human activities on streamflow (Gao et al., 2017c). If the ratio of the two studied variables is constant, the double mass curve is straight; otherwise, a change in the characteristics of the precipitation, runoff or sediment of the studied region occurs at the break point. By establishing a linear regression equation between the precipitation and the sediment load data under original conditions, and then substituting the precipitation data obtained under the changed underlying surface conditions into this regression equation, the calculated sediment load represents the sediment load generated by the natural precipitation in the basin after the change in the underlying surface has occurred (Li et al., 2016). Then, the impact of precipitation change and human activities on sediment discharge can be calculated as follows (Yang et al., 2018):

$$\Delta S_{hum} = S_{ao} - S_{ac} \quad (2)$$

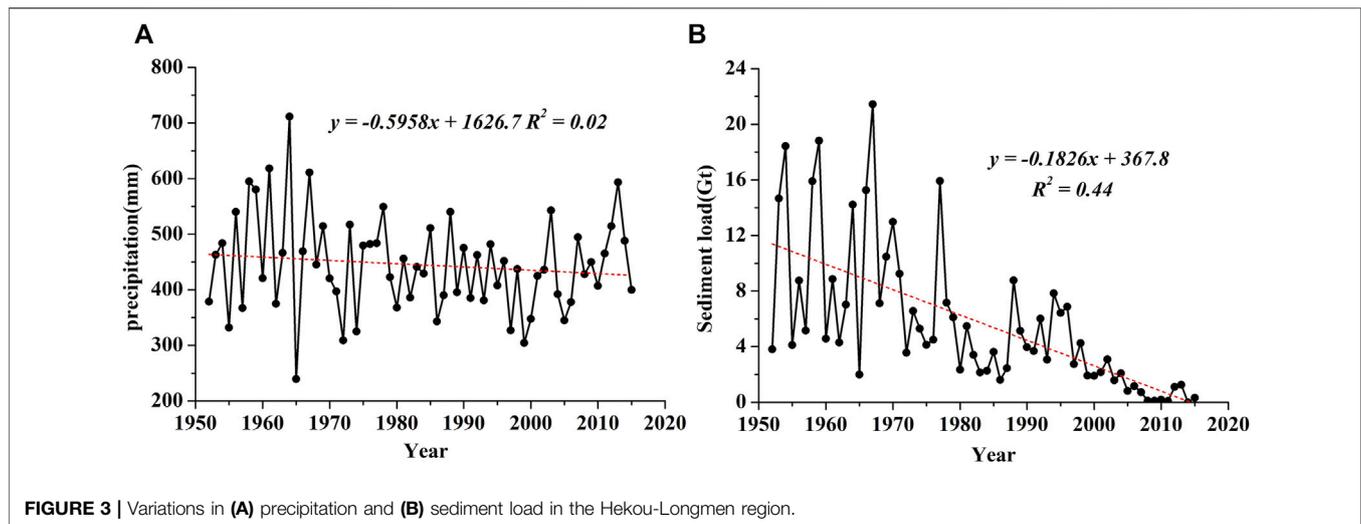
$$\Delta S_{pre} = S_{ac} - S_{po} \quad (3)$$

where ΔS_{hum} denotes the change in the mean sediment discharge due to the effect of human activities (ton); S_{ao} and S_{ac} refer to the observed and calculated sediment discharge of the post-change period, respectively, and are extrapolated using the regression equation for the pre-change period (ton); ΔS_{pre} represents the change in the mean annual sediment discharge due to the effect of precipitation change (ton); and S_{po} is the observed sediment discharge of the pre-change period (ton) (Li et al., 2016).

Check Dam Index

The reservoir index (RI) is a dimensionless indicator proposed by López and Francés (2013) that is represented as follows:

$$RI = \sum_{i=1}^N \left(\frac{A_i}{A_T} \right) \left(\frac{C_i}{C_T} \right) \quad (4)$$



where N is the number of reservoirs upstream of a given gauge station, A_i is the catchment area of each reservoir, A_T is the catchment area of the gauge station, C_i is the total capacity of each reservoir, and C_T is the mean annual streamflow at the gauge station.

Referring to the RI , this study defined the check dam index (CDI), which was used to represent the influence of check dams on the sediment load. The CDI is calculated as follows:

$$CDI = \sum_{i=1}^N \left(\frac{A_i}{A_T} \right) \left(\frac{S_i}{S_T} \right) \quad (5)$$

where N is the number of check dams upstream of a given gauge station, A_i is the controlled area of each check dam, A_T is the catchment area of the gauge station, S_i is the total capacity of each check dam, and S_T is the mean annual sediment discharge at the gauge station.

CDI includes multiple factors affecting sediment yield in a basin, which not only reflects the relationship between the area controlled by check dam and the area of the basin, but also reflects the relationship between the total storage capacity of check dam and sediment transport in the basin. Therefore, CDI can be used to reflect effects of check dam construction on sediment transport.

RESULTS

Changes in Runoff and Sediment Load

According to the results of the Mann-Kendall statistical test analysis, the annual precipitation in the Hekou-Longmen region showed an insignificantly decreasing trend ($p > 0.05$), and the annual sediment load ($Z = -6.87$, $p < 0.01$) showed an extremely significant decreasing trend, as shown in **Figure 3**. Among the 17 tributaries, the sediment load of FCH showed a significant decreasing trend ($p < 0.05$), and the other tributaries showed extremely significant decreasing trends ($p < 0.01$), as shown in **Table 1**. On the basis of Pettitt change-point analysis and double mass curve analysis, two abrupt changes

occurred in the sediment load of the study area; one change occurred in 1979, and one occurred in 1999, as shown in **Figure 4**. As shown in **Figure 2**, large-scale construction of key and medium check dams began in the 1970s, and vegetation coverage in the Hekou-Longmen region increased significantly after 1999. Therefore, based on check dam construction and vegetation restoration, the change in sediment load in the Hekou-Longmen region could be divided into 3 typical periods: the base period (P1, 1952–1979), characterized by a large sediment load and few control treatments; the period mainly impacted by check dam construction (P2, 1980–1999); and the period with comprehensive impact of check dam construction and vegetation restoration (P3, 2000–2017). The decrements in the sediment loads in P2 and P3 were 54.84 and 88.80%, respectively, compared with the sediment load in P1 (**Table 2**).

Effects of Human Activities on Sediment Load

The observed decrease in sediment load was due to both precipitation and human activities. By Pettitt change-point analysis and double mass curve analysis, change points in the sediment load time series were recognized, and regression equations of the precipitation and sediment load during the base period were established (shown in **Table 1** and **Figure 5**). Thirteen tributaries in the Hekou-Longmen region could be divided into the 3 typical periods (P1, P2 and P3), while the other 4 tributaries could be divided into 2 typical periods. By separating the effects of precipitation and human activities by double mass curve analysis, we found that the sediment load averagely decreased by 60.96% in P2 compared to that of P1, among which precipitation led to a decrease of 4.16% and human activities led to a decrease of 56.81%; additionally, the sediment load averagely decreased by 91.76% in P3 compared to that of P1, among which precipitation led to a decrease of 3.73% and human activities led to a decrease of 88.02% (shown in **Figure 6**). The sediment reduction rate in P3 was significantly higher than that in

TABLE 1 | Variation trend of sediment loads in the Hekou-Longmen region.

Code	Basin	Z statistic with sig. Level	Abrupt-change year
1	Hekou-Longmen region	-6.87**	1996
2	HPC	-5.34**	1984
3	KYH	-5.89**	1996
4	TWH	-6.05**	1998
5	ZJC	-5.64**	1982
6	XCH	-4.95**	1996
7	GSC	-5.78**	1996
8	WFH	-7.38**	1986
9	JLH	-5.59**	1978
10	QSH	-5.81**	1978
11	SCH	-6.54**	1978
12	QCH	-4.15**	1996
13	WDH	-5.79**	1979
14	QJH	-4.00**	2002
15	XSH	-6.66**	1981
16	SWH	-6.33**	1983
17	YH	-4.22**	1996
18	FCH	-2.40*	1996

**Indicates significance at $p < 0.01$; *Indicates significance at $p < 0.05$.

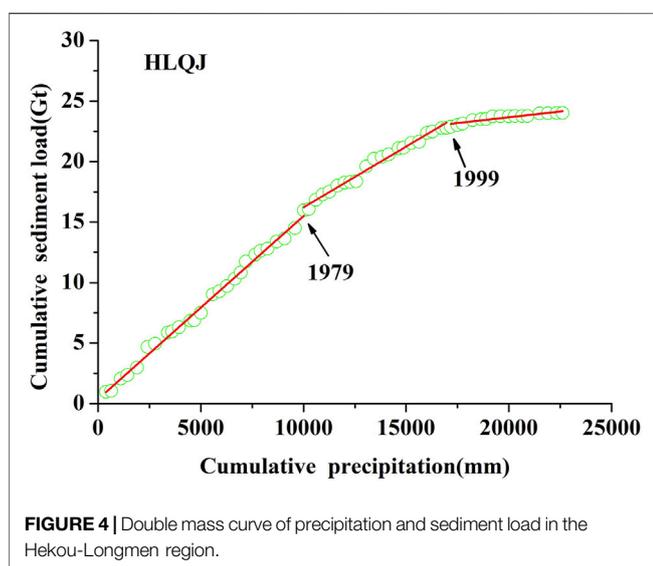


FIGURE 4 | Double mass curve of precipitation and sediment load in the Hekou-Longmen region.

P2, the sediment reduction rate caused by human activities increased significantly in P3, and that caused by precipitation decreased slightly. The average contributions of precipitation and human activities to the reductions in sediment load were 6.79 and 93.21%, respectively. Thus, the reduction effect of human

activities on the sediment load was much more significant than that of precipitation.

Effects of Check Dams and Vegetation Restoration on Sediment Loads

To further investigate the influence of check dam construction and vegetation restoration on sediment load in the basin, the vegetation coverages and *CDIs* of the tributaries in different periods were calculated (shown in **Table 3**). The geomorphology in the Hekou-Longmen region is divided into the first loess hill subregion, the second loess hill subregion and the sandstorm region. Among them, the first loess hill subregion has the most slope land and the heaviest water erosion; the slope land in the second loess hill subregion is less, and part of sloping farmland is transformed into terraced fields, and the water erosion in the second loess hill subregion is strong; the sandstorm region has less water erosion and very strong wind erosion (Huang, 1955). In addition, there are 9 tributaries in the Hekou-Longmen region (such as ZJC) that are located in the first loess hill subregion. The upper reaches of 4 tributaries (such as WDH) are located in the sandstorm region, and the lower reaches of these tributaries are located in the first loess hill subregion. The other 4 tributaries, including YH, are located in the second loess hill subregion (**Figure 1**). According to relevant studies, vegetation coverage values of 0–0.45 can be classified as low-

TABLE 2 | Statistics of precipitation and sediment load.

Period	Annual mean precipitation (mm)	Average annual sediment load (Gt)	Decrement (%)
P1 (1952–1979)	464.16	9.30	
P2 (1980–1999)	418.70	4.20	54.84
P3 (2000–2015)	444.20	1.04	88.80

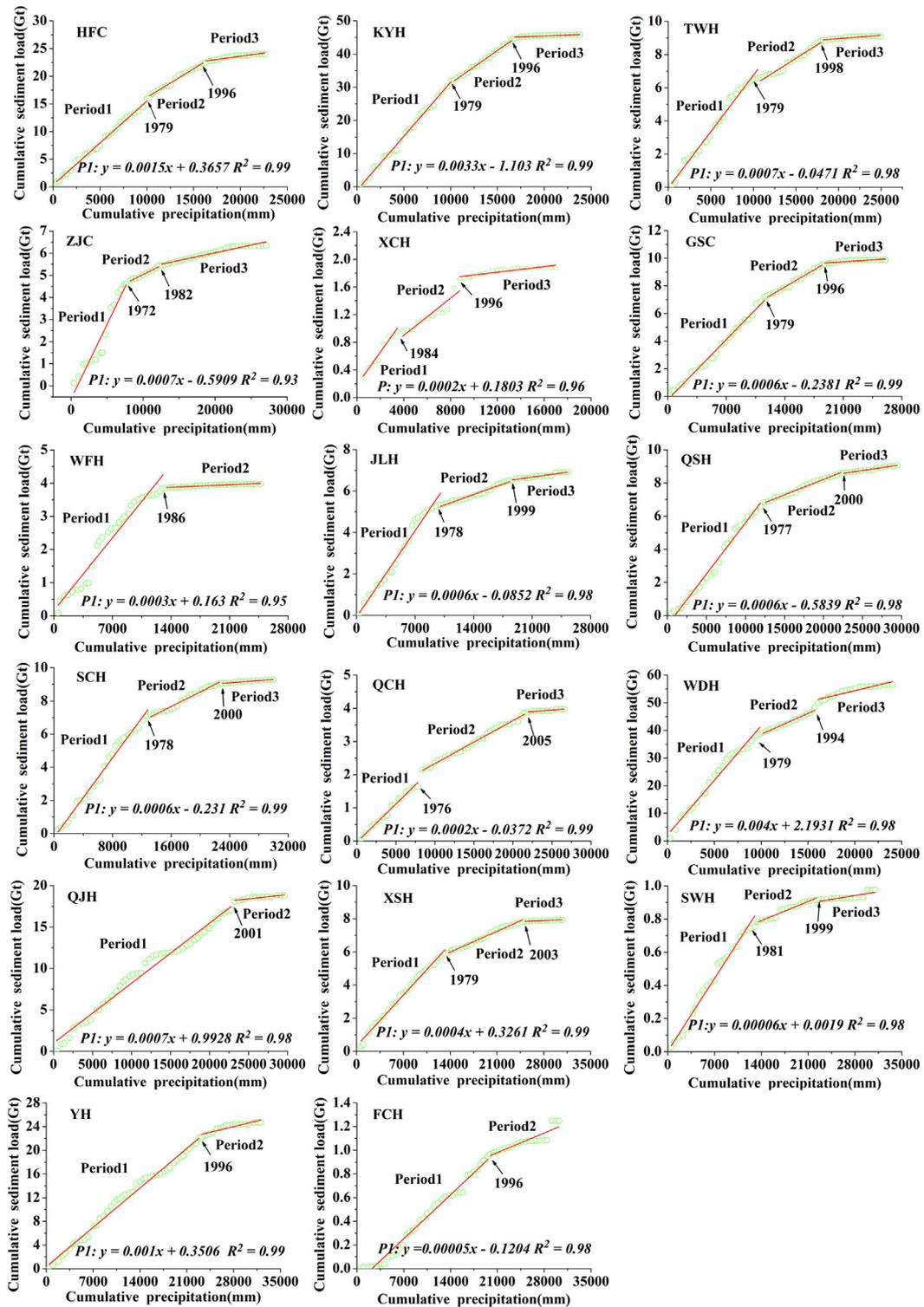


FIGURE 5 | Double mass curves of precipitation and sediment load in tributaries in the Hekou-Longmen region.

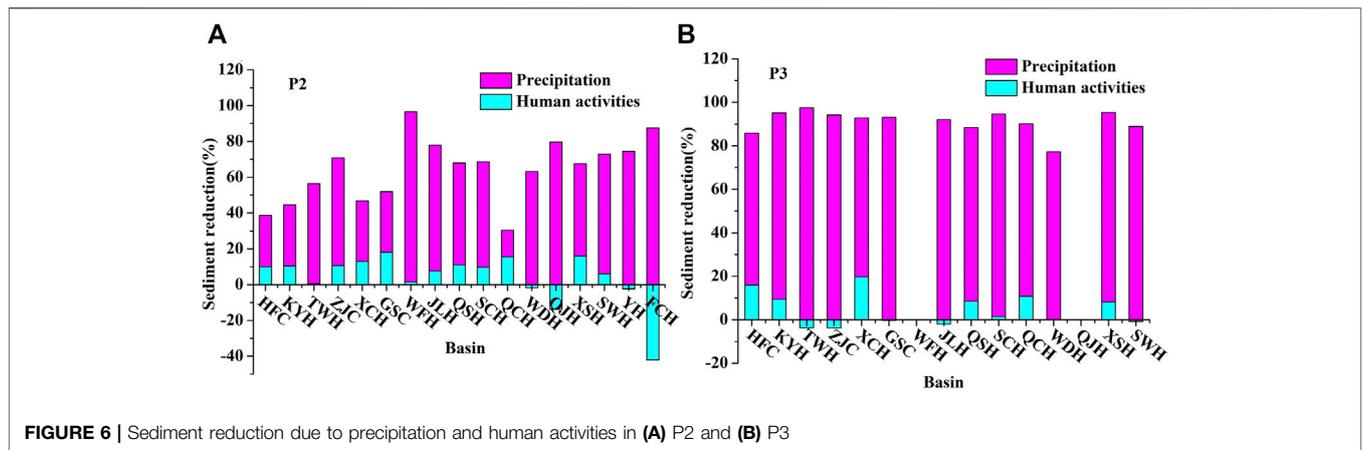


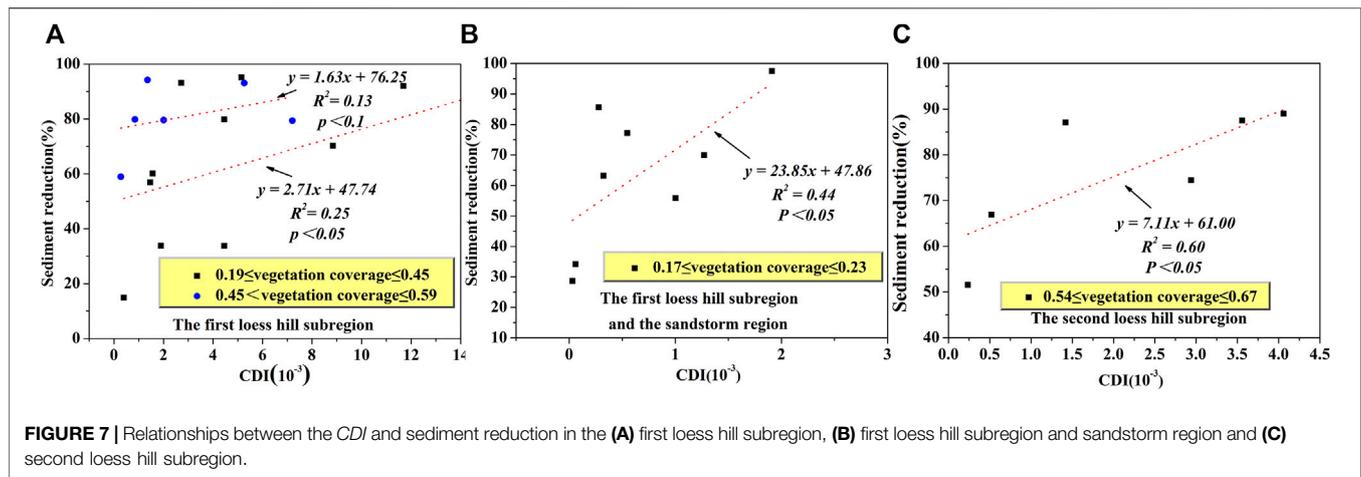
TABLE 3 | Vegetation coverage and the *CDI* in the Hekou-Longmen region.

Region	Basin	Period	Sediment reduction (%)	Vegetation coverage (%)	<i>CDI</i>
The first loess hill subregion	QCH	P2	14.92	0.40	0.40
	QCH	P3	79.36	0.52	7.21
	XCH	P2	33.76	0.40	4.45
	XCH	P3	73.02	0.44	15.60
	GSC	P2	33.80	0.23	1.89
	GSC	P3	93.13	0.30	2.72
	QSH	P2	56.89	0.41	1.46
	QSH	P3	79.86	0.50	0.85
	SCH	P2	58.96	0.53	0.28
	SCH	P3	93.10	0.59	5.26
	ZJC	P2	60.14	0.40	1.56
	ZJC	P3	94.23	0.46	1.36
	JLH	P2	70.24	0.19	8.84
	JLH	P3	92.07	0.29	11.69
QJH	P2	79.59	0.46	2.01	
WFH	P2	95.12	0.42	5.15	
The first loess hill subregion and the sandstorm region	HFC	P2	28.68	0.17	0.03
	HFC	P3	69.95	0.21	1.27
	KYH	P2	34.20	0.19	0.06
	KYH	P3	85.64	0.24	0.28
	TWH	P2	55.81	0.15	1.00
	TWH	P3	97.54	0.21	1.91
	WDH	P2	63.17	0.18	0.32
	WDH	P3	77.15	0.23	0.55
The second loess hill subregion	XSH	P2	51.57	0.54	0.23
	XSH	P3	87.07	0.63	1.42
	SWH	P2	66.93	0.79	0.52
	SWH	P3	88.97	0.81	4.06
	YH	P2	74.44	0.47	2.94
	FCH	P2	87.54	0.67	3.56

level values, and those of 0.45–0.6 can be classified as high-level values (Guo et al., 2019).

The relationships between the *CDI* and the sediment reduction rate caused by human activities were established under different geomorphologic regions and different vegetation coverage (Figure 7). As shown in Figure 7, both of the sediment reduction rates in basins with high and low vegetation coverage in different geomorphologic regions gradually increased with an

increasing *CDI*. In regions with the same geomorphology, the increase in high-vegetation-coverage basins was significantly slower than that in low-vegetation-coverage basins (shown as Figure 7A); a similar regularity was observed among regions with different geomorphological characteristics (shown in Figures 7B,C), which indicated that the contribution of check dam construction to sediment reduction in low-vegetation-coverage basins was higher than that in high-vegetation-coverage basins.



For the state where the *CDI* = 0, the sediment reduction rates of high-vegetation-coverage basins and low-vegetation-coverage basins in the first loess hill subregion were 76.25 and 47.74%, respectively, and vegetation restoration alone could increase the sediment reduction rate by 59.72% (shown in **Figure 7A**). With the same *CDI* = 0, the sediment reduction rate of the basins in both the first loess hill subregion and the sandstorm region was 47.86% (shown in **Figure 7B**). The conditions in the sandstorm region make it difficult to improve the vegetation coverage; thus, it is necessary to further control the sediment by check dams. With *CDI* of 0, the sediment reduction rate of the basins in the second loess hill subregion was 61% (shown in **Figure 7C**), which indicates that without check dams, sediment reduction attributed to vegetation has a certain upper limit.

DISCUSSION

Effects of Vegetation Restoration on Sediment Load

Vegetation restoration not only increases the interception and infiltration of rainfall but also increases the roughness of the land surface, leading to reductions in runoff and sediment yield in a basin (Thompson et al., 2010; Feng et al., 2012). Perennial vegetation is often considered to be effective in stabilizing the soil and reducing erosion (Wang et al., 2015). The results of this study showed that vegetation restoration in different geomorphic regions had different effects on sediment reduction, and sediment reduction effects attributed to vegetation restoration had certain upper limits in most regions. Only when combined with check dams could this sediment reduction benefit increase. The study by Zhao et al. (2017) in the HFC basin also showed that vegetation restoration alone could reduce the sediment load by 31.4%, while vegetation restoration combined with check dam construction could reduce the sediment load by 80%.

The fact that sediment reduction due to vegetation restoration has an upper limit can be attributed to multiple reasons. First, the dry climate and impoverished soil on the Loess Plateau make some areas unsuitable for afforestation; in these areas, the

increase in vegetation coverage has an upper limit (Lu et al., 2012). Second, excessive afforestation can lead to the formation of dry layers in soil, causing ecosystem degradation (Jia et al., 2017; Shao et al., 2018). In addition, when vegetation coverage increases to a certain threshold, the sediment yield is no longer reduced. Liu et al. (2014) showed that there is an exponential relationship between the sediment yield coefficient and the effective vegetation percentage. When the effective vegetation percentage is less than 40%, the improvement in vegetation has a significant impact on sediment reduction in the basin; conversely, when the effective vegetation percentage is more than 70%, the sediment yield coefficient tends to be stable. In addition, the study by Gao et al. (2020) argued that vegetation restoration intensified gravity erosion of the studied channel to a certain extent and increased the sediment yield of the studied basin ensuing. Compared with the anchoring action of a vegetation root system, a soil moisture change on the slope caused by vegetation has a greater effect on intensifying gravity erosion under heavy rainfall events. Therefore, vegetation restoration alone cannot sustainably and effectively reduce sediment loads.

Effects of Check Dam Construction on Sediment Loads

Check dams are usually built to control water and sediment fluxes along stream channels (Nyssen et al., 2004). As an efficient engineering measure used to control soil and water loss erosion, check dams are commonly used worldwide (Mekonnen et al., 2015). Xu et al. showed that the construction of check dams in the YH basin decreased the runoff and sediment load by 15.5–28.9% and 79.4–85.5%, respectively, during the rainy season (Xu et al., 2013). The results of this study showed that the construction of check dams had an obvious reduction effect on sediment load, and the sediment reduction benefits in basins with low vegetation coverage were greater than those in basins with high vegetation coverage; these results were consistent with the conclusions of current researches. The sediment reductions caused by the construction of check dams obtained in studies by Boix-Fayos

et al. (2008), Polyakov et al. (2014) and Shi et al. (2019) ranged from 11.7 to 77%. The sediment reduction benefits of check dams among different basins are related to various factors, such as the basin area, climate and vegetation coverage. It is worth noting that a check dam can quickly intercept sediment and has a significant sediment reduction effect in the early stage of vegetation restoration; this sediment reduction effect gradually decreases with the restoration of vegetation (Zhang et al., 2015; Zhang et al., 2017).

A check dam is a dynamic system, its sediment storage capacity will gradually lose with the siltation of sediments behind the dam, resulting that of the sediment intercept effect of the check dam have very obvious timelines. When the proportion of silted storage of a key check dam reaches 0.77, and the proportion of silted storage of a small or medium check dam reaches 0.88, the check dam will lose its sediment intercept effect (Gao et al., 2014; Liu et al., 2018; Liu et al., 2021). However, Tang et al. (2020) showed that filled check dams were still able to reduce sediment yield by 4–52% under different deployment strategies. The check dam not only has effects on the hydrology and sediment process, but also has some ecological and environmental effects that deserve attention. Bombino et al. (2006) showed that an influence of check dams was found especially in the lower torrent reaches, with a longitudinal diversification of vegetation types and the creation, either immediately up or downstream, of habitats characterized by new biological and ecological formations. Hartman et al. (2016) showed that check dams increase vegetation and standing water at a local scale, and lead to increased greenness at a basin scale.

CONCLUSION

The annual sediment load in the Hekou-Longmen region showed an extremely significant decreasing trend. Two abrupt changes occurred in the sediment load of the study area; one change occurred in 1979 and one occurred in 1999. The changes in the sediment load of the Hekou-Longmen region could be divided into 3 typical periods: the base period (P1, 1952–1979), engineering measure impact period (P2, 1980–1999) and comprehensive impact period (P3, 2000–2017). Among the 17 studied tributaries in the Hekou-Longmen region, the sediment load of FCH showed a significant decreasing trend, and the sediment loads of the other tributaries showed extremely significant decreasing trends. The sediment

load of the tributaries averagely decreased by 60.96% during P2 and by 91.76% during P3. The average contribution of precipitation to sediment load reduction was 6.79% and that of human activities was 93.21%. Compared with P2, the contribution of human activities to the sediment load reduction in P3 increased significantly, while the contribution of precipitation to the sediment load reduction decreased slightly. The construction of check dams has an obvious sediment reduction effect, and this effect is greater in basins with low vegetation coverage than in basins with high vegetation coverage. Vegetation restoration has different effects on sediment reduction among different geomorphic regions, and the sediment reduction effects of vegetation restoration in most regions have certain upper limits. Only when combined with check dams can the sediment reduction benefit of vegetation restoration increase.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

Conceptualization, ZZ and ZL; methodology, ZZ, JC and XZ; formal analysis, ZZ and LC; software, ZZ and KY; ZZ wrote the manuscript and all authors contributed to improving the paper.

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