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Can the Grain-for-Green Program Really Ensure a Low Sediment Load on the Chinese Loess Plateau?

Pengcheng Sun [a], Yiping Wu [a,*], Zhifeng Yang [b], Bellie Sivakumar [c,d,e], Linjing Qiu [a], Shuguang Liu [f], Yanpeng Cai [b]

[a] Department of Earth and Environmental Science, School of Human Settlements and Civil Engineering, Xi'an Jiaotong University, Xi'an 710049, China
[b] State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, Beijing 100875, China
[c] School of Civil and Environmental Engineering, The University of New South Wales, Sydney, NSW 2052, Australia
[d] Department of Land, Air and Water Resources, University of California, Davis, CA 95616, USA
[e] Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai 400 076, India
[f] National Engineering Laboratory for Applied Technology of Forestry and Ecology in South China, Central South University of Forestry and Technology, Changsha 410004, China

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ABSTRACT

The Chinese Loess Plateau is the most seriously eroded area in the world and contributes the vast majority of the sediment that goes into the Yellow River. Since the 1950s, progressive soil and water conservation measures have been implemented—in particular, large-scale ecological restoration has been ongoing since 1999—resulting in a significant reduction of the sediment load. However, the mechanism of the sediment transport dynamics is not fully understood due to multiple and complicated influencing factors including climate change and human activities (e.g., ecological restoration). A challenging question, then, arises: Is the current low sediment level a "new normal" in this era and in the future? To address this question, we selected a typical loess hilly region where considerable ecological restoration has been implemented, and which is regarded as the site of the first and most representative Grain-for-Green program in the Loess Plateau. We investigated the evolution of discharge–sediment relationships in the past decades (1960–2010) and their association with the soil and water conservation measures in this area. The results showed that there was a distinct change in the regression parameters of the commonly used annual discharge–sediment regression equation—a continuously increasing trend of parameter b and a decreasing trend of parameter a, accompanying the ecological restoration. The increase in exponent b (i.e., a steeper slope) implies a potential lower sediment load resulting from low discharge and a potential higher sediment load resulting from large discharge. This finding may question the new normal of a low sediment level and implies the potential risk of a large sediment load during extremely wet years.

1. Introduction

The Yellow River, the second-largest river in China, is the most sediment-laden river on Earth. The annual sediment load of the Yellow River has been estimated to be 0.8 Gt throughout the Holocene and 1.6 Gt in the middle of the 20th century, with this shift mostly being due to land-use intensification driven by increasing population [1–3]. The Loess Plateau (Fig. 1(a)), located by the upper and middle reaches of the Yellow River, is one of the most severely eroded areas in the world due to intense summer rainstorms, steep topography, highly erodible loess soil, and extensive human activities [4,5]. The Loess Plateau is the dominant sediment source area of the Yellow River, and serious soil erosion has shaped the specific geomorphology of the Loess Plateau, which is a fragmented landform with millions of gullies [6,7].

To control the severe soil erosion in the Loess Plateau, several soil and water conservation practices, including both slope conservation measures (e.g., afforestation, grass-planting, and terraces) and channel measures (mainly check-dams), have been implemented since

* Corresponding author.
E-mail addresses: rocky.ypwu@gmail.com, yipingwu@xjtu.edu.cn (Y. Wu).

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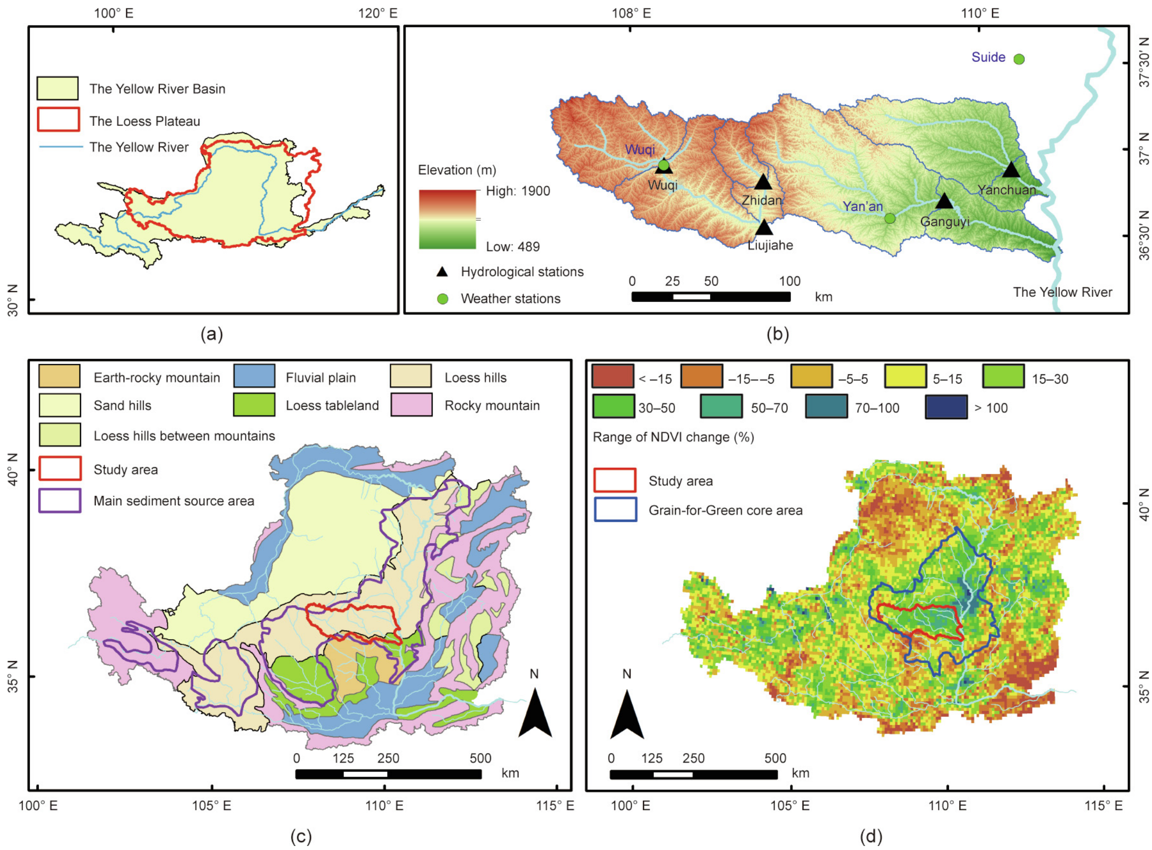

Fig. 1. Location and environment description of the Loess Plateau and the study area. (a) Location of the Loess Plateau; (b) an overview of the study area; (c) landforms of the Loess Plateau; (d) the range of the growing season (June–September) vegetation coverage change (about 30 years during 1982–2010) reflected by normalized difference vegetation index (NDVI).

the 1950s [8–10]. The largest revegetation program in the world, the Grain-for-Green program, was initiated in 1999 in the Loess Plateau, and induced a significant increase of vegetation coverage [11,12]. During the past five decades, the amounts of sediment and streamflow have decreased along the Yellow River mainstream and most of its tributaries, and the causes of these changes have received considerable attention [6,13,14]. Some studies have tried to quantitatively assess these changes, and have found that human impact is more important than climate change in driving changes in sediment yield in this area [15–17].

In the field of sediment studies, the discharge–sediment relationship (herein, *discharge* refers to streamflow discharge) is a powerful tool for understanding and evaluating complex hydrological and erosion processes, and can serve as a useful indicator of river system function [18,19]. The discharge–sediment relationship depends on the topography, soil property, and land use; thus, it may change over time as a result of many disturbances including wildfire, drought, dam construction, and land-use change [20–24].

Is the discharge–sediment relationship in the Loess Plateau changing, especially under the continuous ecological restoration programs (e.g., the Integrated Management of Small Watersheds and Grain-for-Green programs)? How does the relationship change, and what are the implications of such change? In an attempt to address these important questions, we selected a typical loess hilly region where the representative and progressive ecological restoration program (Grain-for-Green program) has been implemented. We adopted the commonly accepted discharge–sediment regression equation to detect the relationship change with a step-wise manner in time to reflect its evolution during the continuous ecological restoration programs.

2. Materials and methods

2.1. Study area

The study region is located in the middle of the Loess Plateau and includes the headwater areas of the Beiluo River, the Yanhe River, and the Qingjian River (Table 1 and Fig. 1(b)). There are three reasons for selecting this region. First, the study area is located in the loess hilly region, which suffered the most severe soil erosion in the Loess Plateau and was the main sediment source area of the Yellow River (emphasized with purple, Fig. 1(c)) [9,25]. Second, this region had undertaken the strongest soil and water conservation measures, and was the first and representative region that implemented the Grain-for-Green program. Its vegetation coverage for the growing season increased significantly as a result of the program, with a higher increasing rate (34% during 1982–2010) than other parts of the Loess Plateau (12% during 1982–2010) (Fig. 1(d)) [11]. Third, headwater areas are valuable but vulnerable because they are usually more sensitive to environmental change and are the major water and sediment source in a watershed [20,26]. Technically, the study region can be identified by overlapping the main sediment source areas with the areas implementing the Grain-for-Green program (Figs. 1(c) and (d)). This study area is covered by thick loess, which is an erosion-prone silty-loam soil [16], and the average annual sediment yield in this region ranges from 6700 to more than 11 100 $t\cdot km^{-2}$, indicating serious soil erosion (Table 1). The average annual precipitation in the study region is approximately 500 mm and about 80% of the annual precipitation falls during the wet season (May to September), based on the 51-year (1960–2010) records. In this area, most of the summer

Table 1
Watershed characteristics and data.

Watershed	Gaging station	Area (km^2)	Period of available annual data	Average discharge ($mm\cdot a^{-1}$)	Discharge range ($mm\cdot a^{-1}$)	Average sediment concentration ($kg\cdot m^{-3}$)	Peak sediment concentration ($kg\cdot m^{-3}$)	Annual sediment load ($t\cdot km^{-2}$)	Sediment load range ($t\cdot km^{-2}\cdot a^{-1}$)
Beiluo River	Wuqi	3 408	1963–2010	28.7	12.0–67.2	317.3	1 220	11 133.6	60.5–59 338.8
Beiluo River	Zhidan	774	1965–2010	37.3	9.7–84.4	230.7	941	10 712.1	13.7–42 894.1
Beiluo River	Liujiahe	7 325	1960–2010	31.8	16.8–72.6	234.1	997	8 675.4	483.3–40 409.6
Yanhe River	Ganguyi	5 891	1960–2010	34.3	17.9–85.2	170.6	1 203	6 747.0	220.7–30 894.6
Qingjian River	Yanchuan	3 468	1960–2010	38.5	17.9–89.4	193.9	1 150	8 728.1	157.4–19 872.9
Entire area	–	16 684	1960–2010	34.1	18.3–75.4	206.3	–	8 005.4	345.7–29 379.2

precipitation falls with high intensity, causing intensive soil erosion and a high sediment load [7,27]. The peak sediment concentration can reach as high as 1220 $kg\cdot m^{-3}$ (Table 1) [28]. As a result, these extreme rainfalls dominate the sediment delivery in this area, and the sediment transported during these extreme events can contribute more than 90% of the annual sediment load [29]. For example, a rainfall storm hit the Beiluo River Basin on 31 August 1994 with 383 mm of precipitation in 12 h and an intensity of 120 $mm\cdot h^{-1}$, causing peak sediment concentrations of 832, 787, and 844 $kg\cdot m^{-3}$ for the Wuqi, Zhidan, and Liujiahe Stations, respectively [30]. The sediment transported in this single event contributed about 58.5%, 62.2%, and 55.6%, respectively, of the 1994 sediment delivery for the three stations.

2.2. Data sources

The geomorphology and landform data were obtained from the Loess Plateau Data Center at the National Earth System Science Data Sharing Infrastructure of China [31]. The discharge and the sediment load were measured with a daily frequency by an agency affiliated with the Yellow River Water Resources Commission, and we used the released annual data with quality control by the agency for the five hydrological gaging stations (Wuqi, Zhidan, Liujiahe, Ganguyi, and Yanchuan). Daily precipitation data for three weather stations (Wuqi, Yan'an, and Suide) were obtained from the National Meteorological Information Center [32]. The normalized difference vegetation index dataset (NDVI)-3rd generation dataset (NDVI3g) in the framework of global inventory modeling and mapping studies (GIMMS) was obtained from the National Aeronautics and Space Administration (NASA) Ames Ecological Forecasting Lab [33,34], and NDVI data covering the growing season (June to September) were used to reflect the intensity of vegetation construction. Information on the cumulative area with ecological restoration measures was collected from Zhang [28] and Yao et al. [35].

2.3. Sediment rating curves

Sediment rating curves are usually used to reflect the patterns of the supply and transport of sediment over multiple timescales because they can describe the relationship between sediment and discharge for a specific location [36–38]. These curves are generally expressed as follows:

$$C_s = a \cdot Q^b \tag{1}$$

where C_s is the sediment concentration ($kg\cdot m^{-3}$), Q is the discharge ($m^3\cdot s^{-1}$), and a and b are the rating parameters of the sediment curve.

Similarly, there is a power-law relationship between the annual sediment load (L_s) and the discharge (Q) [21,39]. In this study, we normalized the discharge by the geometric mean of the sample discharge (Q_{GM}), and then used the least squares method to fit the power-law equation, as follows [22]:

$$L_s = \hat{a} \cdot \hat{Q}^{(b+1)} \tag{2}$$

where L_s is the annual sediment load ($\times 10^6$ t), $\hat{Q}$ is the geometric mean annual discharge, and $\hat{a}$ is the equation regression parameter ($\times 10^6$ t).

As shown above, sediment rating curves are largely a product of the patterns of the supply and transport of sediment over time, and the parameters a and b are often dependent on watershed features [36]. The parameter b has been associated with the erosive power of the river, and is dependent on channel morphology, the grain-size distribution of sediment particles, and the extent of new sediment sources [36,40,41]. The parameter a can be taken as an index of erosion severity, and is associated with watershed sediment production; it has a high value in areas that are covered with easily erodible materials [22,36]. To investigate the features of the discharge–sediment relationship over time, we used 11-, 15-, and 20-year moving windows to resample the annual discharge and sediment load datasets and derive the parameters of the sediment rating curve using least squares regression. Taking the 11-year moving window as an example, the regression results (i.e., parameters of the rating curve) for a specific year (e.g., 1965) were derived from 11 years of data with the specific year (1965) at the middle of the resampled data period (e.g., 1960–1970).

2.4. Trend analysis

In this study, we employed the widely accepted nonparametric Mann–Kendall (MK) test [42,43] to detect the presence of a trend, and assessed its significance. A Z statistic was obtained from the MK test, where a negative value of Z indicated a downward trend, while a positive value indicated an upward trend. We then used the nonparametric median-cased linear model method proposed by Sen [44] to estimate the magnitude of a trend, β. The nonparametric method developed by Pettitt [45] was used to detect a change-point.

3. Results

3.1. Trends and change-points of discharge and sediment

The annual discharge and sediment load at five gaging stations and from the entire study area are displayed in Fig. 2, which shows great inter-annual variations in discharge and sediment load. For example, the annual discharge at Liujiahe Station ranged from 1.231×10^8 m^3 (16.8 mm) in 2006 to 5.321×10^8 m^3 (72.6 mm) in 1994, while the sediment load ranged from 3.5×10^6 t (483.3 t·km^{-2}) in 2008 to 2.960×10^8 t (40 409.6 t·km^{-2}) in 1994. Fig. 2 shows that there has been a remarkable decrease of both discharge and sediment load; Table 2 lists a further statistical analysis of their trends using the MK nonparametric test. Decreasing trends were detected in annual sediment load and sediment concentration at all five gaging stations and for the entire area at the 0.01 significance level. Sen's test showed that the decreasing rate of annual sediment load varied from −100.8 to −385.4 t·km^{-2}, with a −135.0 t·km^{-2} decrease for the entire area. Significant decreasing trends were also detected in the annual discharge at four of the five stations and in the entire area ($p < 0.01$). Although a decreasing trend was also noted for Yanchuan Station, this trend was not significant at the 0.05 significance level. Overall, the decreasing rate of annual discharge varied from −0.2 to −0.7 mm, with a −0.3 mm decrease for the entire area.

The results from the change-point analysis of the annual discharge and sediment load are shown in Table 3. Pettitt's test showed that the change-point years of both the annual discharge and sediment load were statistically significant ($p < 0.05$). The change-point years of the sediment load for Wuqi, Zhidan, Liujiahe, Ganguyi, and Yanchuan were found to be 2001, 1996, 2002, 1996, and 2002, respectively. Over the past 51-year period, all the change-points were around 1999 when the large-scale Grain-for-Green restoration program was initiated in the Loess Plateau (Tables 3 and 4), which supports the reasonability of our analysis and results. The relative decrease in the average annual discharge before and after the change-point for the five stations ranged from 30.1% to 49.0%, with a 32.4% decrease for the entire area. The decrease in the annual sediment load for the five stations ranged from 66.1% to 83.1%, with an 81.4% decrease for the entire area. The decrease in sediment was much larger than that of discharge, which can be explained by the discharge–sediment relationship. As shown in Eq. (2) and Fig. 3, the exponent parameter ($b + 1$) in the discharge–sediment relationship for all the stations was larger than 1, which indicates that a reduction in discharge results in a greater reduction in sediment load.

3.2. Discharge–sediment relationships at the annual scale

Although sediment rating curves are in the form of a power function, the log-transformed formula is linear. Based on the observed annual discharge and sediment load, we derived the

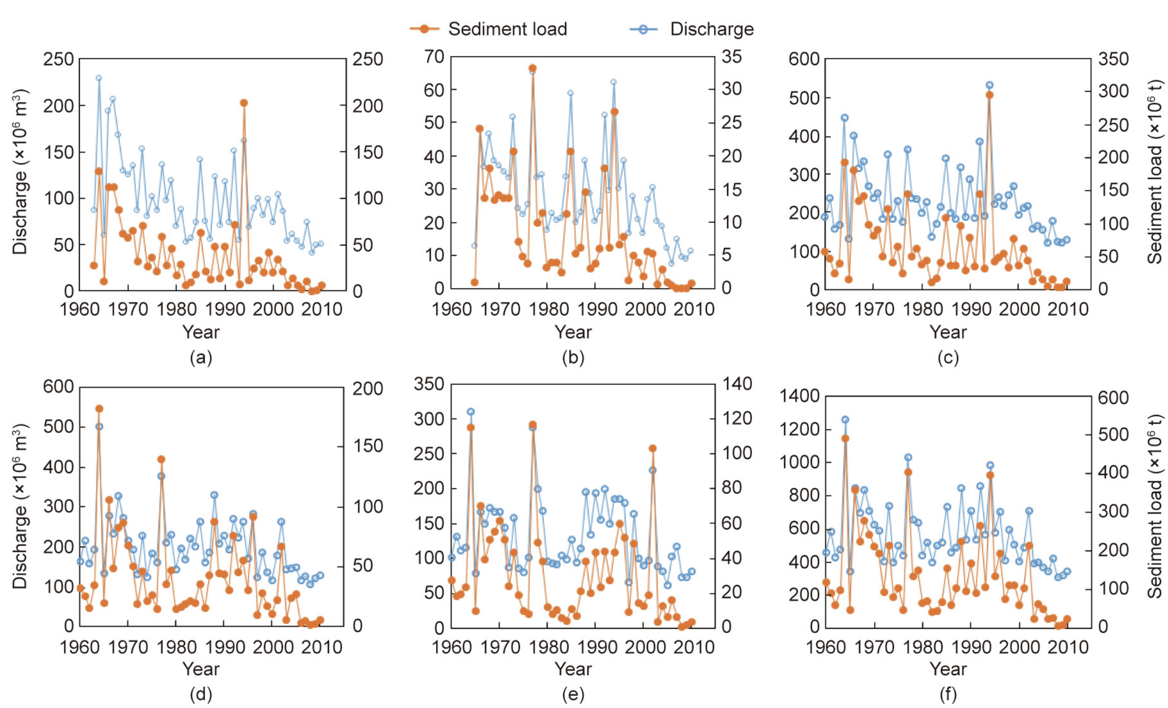

Fig. 2. Annual discharge and sediment load at five stations: (a) Wuqi, (b) Zhidan, (c) Liujiahe, (d) Ganguyi, and (e) Yanchuan, and from (f) the entire study area.

Table 2
Trend analysis of annual discharge, sediment concentration, and sediment load during the 51-year (1960–2010) period using the MK nonparametric test.

Gaging station	Annual discharge		Annual sediment concentration		Annual sediment load	
	MK, Z	Sen's, β (mm)	MK, Z	Sen's, β ($kg\cdot m^{-3}$)	MK, Z	Sen's, β ($t\cdot km^{-2}$)
Wuqi	-4.3^{***}	−0.5	-4.7^{***}	−7.6	-4.4^{***}	−322.9
Zhidan	-4.0^{***}	−0.7	-5.1^{***}	−7.4	-4.4^{***}	−385.4
Liujiahe	-2.6^{**}	−0.2	-4.1^{***}	−4.4	-3.7^{***}	−169.9
Ganguyi	-2.8^{**}	−0.3	-3.0^{**}	−2.8	-3.0^{**}	−100.8
Yanchuan	-1.7^{NS}	−0.2	-3.0^{**}	−3.2	-2.7^{**}	−121.4
Entire area	-2.6^{**}	−0.3	-3.2^{***}	−3.2	-3.0^{**}	−135.0

** and *** indicate the 0.01 and 0.001 significance levels, respectively; NS indicates that the significance level exceeds 0.05.

Table 3
Summary of change-point analysis of annual discharge and sediment load.

Gaging station	Annual discharge				Annual sediment load			
	Change-point year	Pre (mm)	Post (mm)	Change (%)	Change-point year	Pre ($t\cdot km^{-2}$)	Post ($t\cdot km^{-2}$)	Change (%)
Wuqi	2001***	31.4	16.9	−46.3	2001***	13 188.6	2 229.0	−83.1
Zhidan	1996***	43.9	22.4	−49.0	1996***	14 245.4	2 635.9	−81.5
Liujiahe	2002*	34.0	19.9	−41.6	2002***	9 969.3	1 720.6	−82.7
Ganguyi	1996**	37.9	24.8	−34.6	1996***	8 242.5	2 794.6	−66.1
Yanchuan	1996*	42.0	29.3	−30.1	2002*	10 006.8	1 855.4	−81.5
Entire area	1996**	37.3	25.2	−32.4	2002**	9 177.6	1 705.2	−81.4

*, **, and *** indicate the 0.05, 0.01, and 0.001 significance levels, respectively. "Pre" refers to the period from the beginning year of the data series to the year in the "Change-point year" column and "Post" refers to the period from the year when "Pre" ends. "Change" is the relative change in mean annual discharge/sediment load before and after the change-point year, expressed as a percentage.

Table 4
Cumulative area of major soil and water conservation measures in the three subregions of the study area.

Watershed/gaging station	Year	Terraces (km^2)	Farmland created by check-dams (km^2)	Afforestation (km^2)	Grass-planting (km^2)	Total area (km^2)	Proportion of affected area (%)
Upper Beiluo River/Liujiahe Station	1959	3	1	52	2	58	0.8
	1969	35	5	164	13	217	3.0
	1979	85	13	285	36	419	5.7
	1989	134	13	550	167	864	11.8
	1996	202	19	834	267	1322	18.0
	2006	262	20	1492	678	2452	33.5
Yanhe River/Ganguyi Station	1959	4	5	41	0	50	0.8
	1969	47	16	161	4	228	3.9
	1979	98	29	287	18	432	7.3
	1989	174	38	841	145	1198	20.3
	1999	185	24	1314	114	1637	27.8
	2006	296	32	2025	344	2697	45.8
Qingjian River/Yanchuan Station	1959	7	1	13	0	21	0.6
	1969	42	3	47	3	95	2.7
	1979	93	7	111	6	217	6.3
	1989	146	23	596	26	791	22.8
	1999	161	27	698	80	966	27.9
	2006	243	48	1213	230	1734	50.0

This table only lists the three watersheds where the three stations (Liujiahe, Ganguyi, and Yanchuan) are located; the other two watersheds where two stations (Wuqi and Zhidan) are located were excluded here due to the non-availability of data.

sediment rating parameters ($\log \hat{a}$ and b) using the least squares step-wise regression method, together with the corresponding squared correlation parameters (R^2), for the period 1960–2010. As described previously (Section 2.3), we used 11-, 15-, and 20-year moving windows to resample annual datasets and implement the regression. Because the results (the parameters of the sediment rating curve) were quite similar using three kinds of moving window (see Fig. S1 in the Supplementary data), we only present the result obtained using the 11-year moving window in Fig. 3.

As Fig. 3 indicates, the squared correlation parameters for most curves were greater than 0.6, and all regressions were significant ($p < 0.05$). Both parameters and the R^2 value revealed significant time-dependent trends over the 51-year study period. A similar tendency was found for parameter b for all the stations and for the entire area. As shown in Fig. 3, the initial b values for all the stations were roughly around 1 for about 30 years since the beginning of the data, with a continuous mildly increasing trend, although there was a relatively higher b value for some years during the 1970s through the 1980s, especially for the Liujiahe and Yanchuan stations (see Fig. 3). It is also clear that the b value increased dramatically for almost 20 years starting in the late 1990s, although the magnitude varied among the stations. Using the MK trend test, we detected a significant increasing trend in b over time ($p < 0.05$) on the rating curves. For the entire area, the value of b before and after the sediment load change-point year was 1.09 and 2.63, respectively. However, the trends of $\log \hat{a}$ over time were much more complicated; a significant decrease in $\log \hat{a}$ ($p < 0.01$) was detected for four of the five stations, while the changes for Wuqi

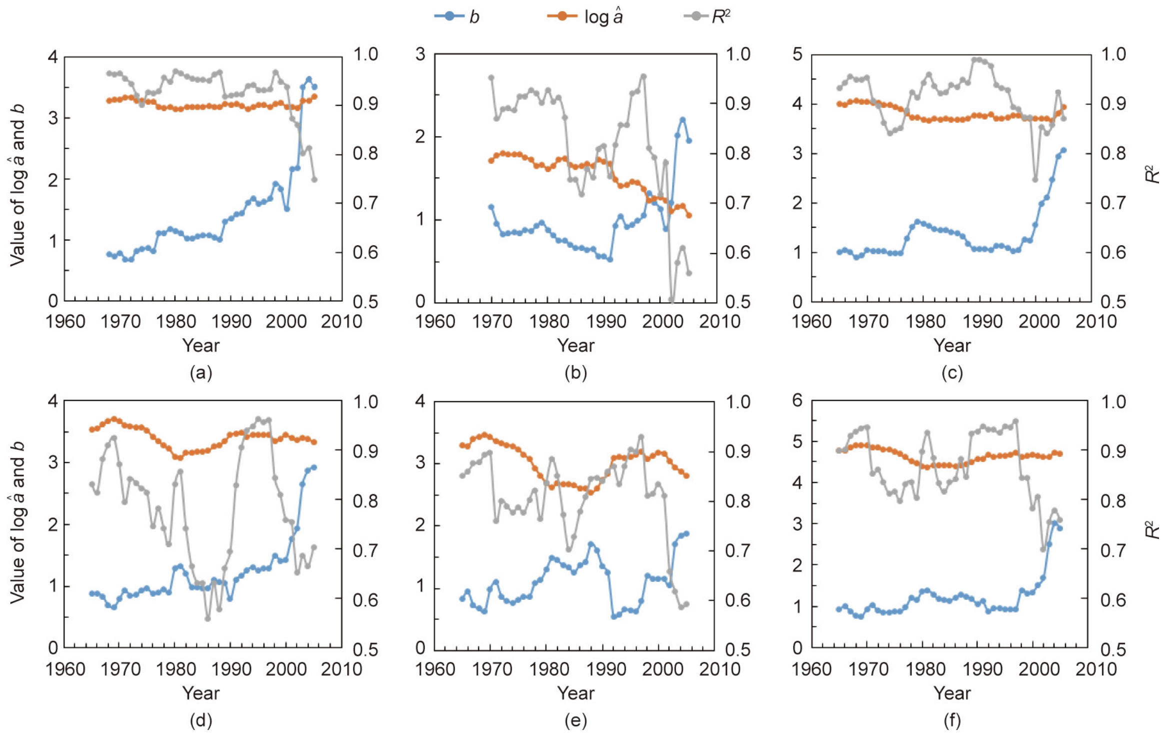

Fig. 3. Trends of the parameters of sediment rating curves at five stations: (a) Wuqi, (b) Zhidan, (c) Liujiahe, (d) Ganguyi, and (e) Yanchuan, and in (f) the entire study area. The parameters in one specific year (t) are from the regression (Eq. (2)) between the geometric mean annual streamflow (Q/Q_{GM}) and the annual sediment load L_s ($\times 10^6$ t) using the specific dataset covering year ($t-5$) to year ($t+5$). t starts at 1965 for (c) Liujiahe, (d) Ganguyi, (e) Yanchuan, and (f) the entire study area, at 1968 for (a) Wuqi, and at 1970 for (b) Zhidan, respectively, due to different data availability periods.

Station and for the entire area were very small and can be viewed as negligible. In addition, we found a decreasing trend in R^2 for all the stations and for the entire area, especially toward the end of the 51-year period (Fig. 3). The decrease in R^2 shows that the power-law relationship can explain less data variance, indicating that the discharge–sediment relationship has become more complicated.

4. Discussion

4.1. Potential causes of the discharge–sediment relationship changes

Changes over time in the sediment rating curve parameters, log $\hat{a}$ and b, have been noted for many river systems, and there is a general assumption that these changes reflect the alteration of the erodibility, the supply of sediment in the watershed, and the power of the river to erode and transport sediment [22,36]. For a specific area, changes in sediment rating curves are typically attributed to alterations in river suspended-sediment fluxes, which are in turn related to the sediment production of an area [46,47].

Fig. 4 presents the annual rainfall for the three weather stations in the study area and in the entire area. The one-way analysis of variance demonstrated limited variation in the annual precipitation, with no significant difference between any of the periods ($p > 0.05$) for all three stations. Anthropogenic activity has been shown to be the most active factor influencing sediment production in the Loess Plateau [16]. Large-scale soil and water conservation measures have been implemented in the Loess Plateau, initiated by government-sponsored conservation programs and ecological restoration campaigns [48–50]. The area in which soil and water conservation measures are being taken has increased since 1959, especially from the 1970s to 1980s and during the 2000s, owing to a few programs: the Soil Erosion Control in Highly Erodible Areas program in the 1970s, the Integrated Management of Small Watersheds program in 1982, and the Grain-for-Green program in 1999. The sediment retained inside a check-dam can form farmland, and the size of such farmland increased significantly during the 1970s and 1980s in our study area (Table 4). Furthermore, slope conservation measures (mainly afforestation) have surged since the late 1990s, with the percentage of treated land increasing from 0.6%–0.8% in 1959 to 33.5%–50.0% in 2006 (Table 4). Slope conservation measures can reduce soil loss from hillslopes by increasing vegetation cover (afforestation and grass-planting) or by reducing slope lengths and gradients by leveling ground surfaces (i.e., forming terraces) [9,51]. Check-dam systems built up in gullies or channels can both control soil erosion by stabilizing gully/channel beds, consolidating hillslopes, and/or decreasing bed slope gradient, and directly reduce sediment load by trapping sediments or regulating sediment transport [52,53]. In addition, the slope conservation measures and check-dams have reshaped the sedimentological connectivity and thus affected sediment transport at the catchment scale [54–56]. A large number of studies have confirmed the major effects of these conservation measures, and have suggested them to be the dominant factors in the observed sediment reduction [16,57–60]. Thus, it is necessary and significant to examine the connection between the change in the sediment rating curves and these remarkable and effective conservation measures. Previous studies [36,60–62] have indicated that the parameter a represents an index of sediment supply and watershed erosion severity, and that a high value indicates the ready availability of sediment that can be transported easily. The exponent parameter b is regarded to be an index of the erosive power and transport capacity of stream water, with a high value indicating an increase in the sediment transport capacity of a river stream, and with a small increase in discharge leading to a strong increase in erosive power. A lower supply of erosive materials as a result of conservation measures would lead to a discharge–

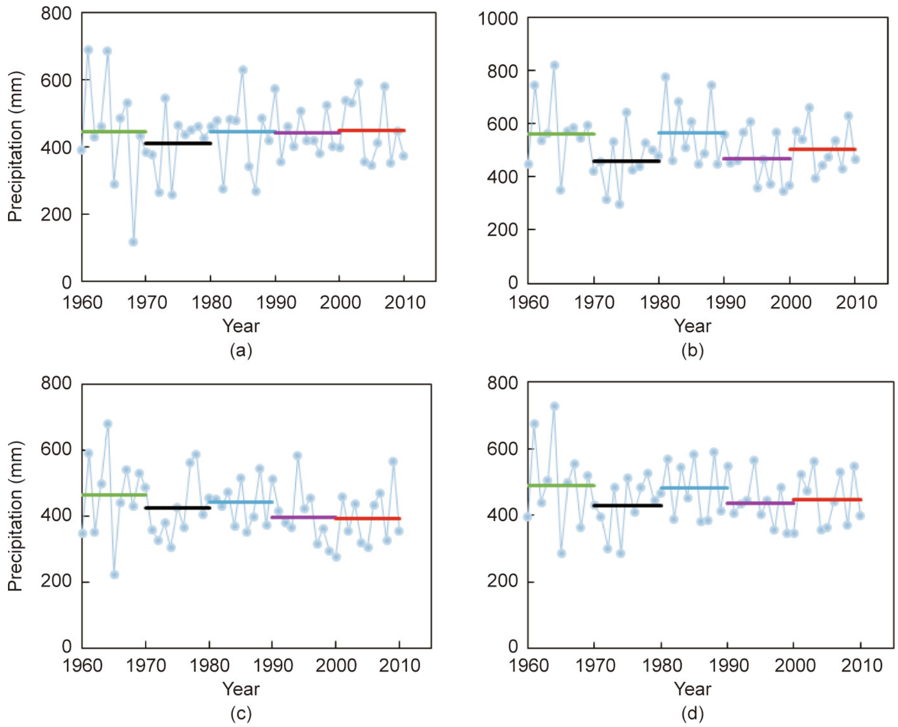

Fig. 4. Change in annual precipitation at three weather stations: (a) Wuqi, (b) Yanan, and (c) Suide, and in (d) the entire area.

sediment relationship with a higher *b* value and a lower *a* value [40,60]. Thus, we concluded that the change in the regression parameters can mostly be attributed to regional soil and water conservation practices.

As shown in Fig. 3, the relatively higher *b* and the relatively lower $\log \hat{a}$ in some years during the 1970s, 1980s, and 1990s are consistent with the expected effects of the Soil Erosion Control in Highly Erodible Areas program and the Integrated Management of Small Watersheds program in this period, whereas the significant increase in *b* and the decrease in $\log \hat{a}$ since 2000 are consistent with the Grain-for-Green program that was started in 1999. These results indicate that parameters $\log \hat{a}$ and *b* could very well represent the effects of ecological restorations. Table 4 and Fig. 3 also show that $\log \hat{a}$ decreased more sharply when and where more sediment was retained by check-dams. For example, the dramatic decrease in parameter $\log \hat{a}$ during the 1970s and 1980s by 24%, 34%, and 52% in the Upper Beiluo River, Yanhe River, and Qingjian River, respectively, is consistent well with the area of newly created farmland by check-dams—8, 13, and 20 km^2 in the three watersheds in the corresponding time period. In addition, the remarkable increase in parameter *b* since the late 1990s is consistent with the implementation of the Grain-for-Green program, which is considered to have played a key role in sediment reduction in the Loess Plateau [6]. Therefore, it can be seen that check-dams had a greater impact on the decrease in parameter *a*, while slope conservation measures exerted a stronger influence on the increase in parameter *b*. Zheng [10] has reported the effects of check-dams on the reduction of rating coefficient *a* in the proportional discharge–sediment relationship. Yan et al. [63] used two paired small watersheds to examine the discharge–sediment relation, and found that check-dams, rather than slope conservation measures, affect parameter *a*. However, Gao et al. [64] has reported that the variability of discharge–sediment relationships is mainly regulated by the vegetation restoration. In our present study, the effects of slope conservation measures on parameter *a* are still uncertain, because the mild decrease of *a* during the 2000s may be attributed to both check-dams and slope conservation measures in this period. Some recent studies have tried to predict the two parameters *a* and *b* using watershed features, including watershed topography and soil erodibility, river channel morphology, and the grain size of sediment [24,65,66]. For example, Heng and Suetsugi [66] examined the connection between five watershed parameters, including annual discharge (Q_a), mean slope gradient (S_c), mean mainstream bed slope gradient (S_r), the land cover factor (C_{USLE}), and the soil erodibility factor (K_{USLE}), with sediment rating curve parameters using the Lower Mekong Basin as a case. To sum up, it would be beneficial to understand and quantify the response of the discharge–sediment relationship to different human activities (e.g., revegetation, terraces, and check-dams), making this a good subject for deep investigation in future studies.

4.2. Implications of the discharge–sediment relationship

Sediment rating curves at the annual scale from different time periods were used to analyze the implications. As shown in Fig. 5, the slope of the regression curves increased over time with the increase of parameter *b*. At the same time, there was a critical point—the crossing point of the previous curve and the recent curve. Less sediment would be transported in hydrological years whose discharge was less than the critical discharge, while in years with discharge greater than the critical discharge, much more sediment would be transported. However, as the discharge was reduced dramatically in the Loess Plateau due to substantial environment changes, including climate change and anthropogenic activities, there were only five events (i.e., 2001 in Wuqi and Liujiahe, and 2002 in Liujiahe, Yanchuan, and the entire study area) with a discharge exceeding the critical point (i.e., the crossing point between the 1960–1970 relationship and the 2000–2010 relationship). As shown in Fig. 5, four of these five events (i.e., 2001 in Wuqi, 2001 in Liujiahe, 2002 in Yanchuan, and 2002 in the entire study area) transported more sediment than predicted using the 1960–1970 discharge–sediment relationship, while the level of sediment transported by the fifth event (i.e., 2002 in Liujiahe)

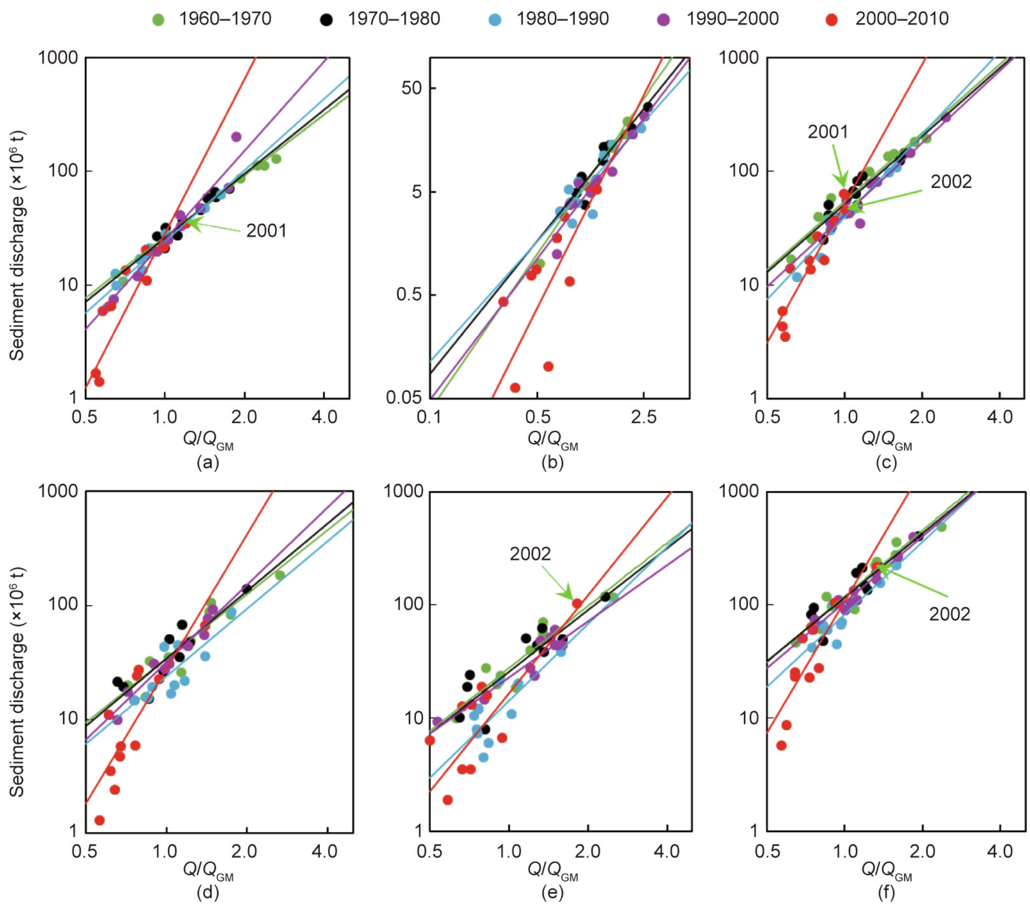

Fig. 5. Annual scale sediment rating curves at five stations: (a) Wuqi, (b) Zhidan, (c) Liujiahe, (d) Ganguyi, and (e) Yanchuan, and in (f) the entire study area during different time periods.

remained nearly the same. These findings suggest that high sediment loads are still likely to occur in the future.

As mentioned above, an increase of b means an increase in the erosive power and sediment transport capacity of the river stream. Some studies have revealed that the disequilibrium in the fluvial sediment system moves toward an equilibrium condition [67–69]. When the sediment from the upper stream is less than the sediment-carrying capacity, more sediment particles are captured to meet the increased sediment-carrying capacity of the water flow in the channel, resulting in an equilibrium condition. As a result, an increase in b might result in the intensification of channel erosion due to higher sediment carrying capacity and thus threatens the ecosystem sustainability of the upper headwaters [36,60]. Perks and Warburton [70] reported that the b value decreased after a river cut-off, implying that a larger b value indicates stronger channel erosion. In our study area, Zhang et al. [29] found a positive trend in the proportion of flood events with clockwise flood runoff-sediment load hysteresis, indicating that potential erosion of the channels might have played an increasingly important role in sediment delivery because serious in-channel erosion would alter the hysteresis loops from anti-clockwise to clockwise [71,72]. In the Loess Plateau, a great deal of farmland has been created by check-dams across ephemeral river channels. In addition, some new farmland were recently created across channels by the Land Consolidation projects in this region in order to mitigate the shortage of cultivated land caused by the ecological restoration projects [73–75]. Intensified channel erosion could cause serious damage to this kind of farmland and provide sediment to downstreams, given that most channels are unprotected and are susceptible to erosion under extreme precipitation and runoff. Therefore, a sediment load with greater intensity is likely if many more sediment particles are eroded and transported from channels by relatively large discharges under the new sediment rating curves, even with good soil and water conservation measures on the slope. In the summer of 2017, a serious rainfall storm hit the nearby Zizhou County, about 30 km north of the study area. In this rainfall storm event, many check-dams and a considerable amount of newly created land in the channels were destroyed, contributing a great deal of sediment to the river [76]. Wang et al. [77] reported that runoff from small gullies had a lower sediment concentration while water in the main stream had a higher sediment concentration, and that the river bank was an important source of sediment. All of these phenomena indicate that gullies, check-dams, and river banks could become important sources of sediment in the post-revegetation period.

5. Conclusions

We investigated the change in the discharge–sediment relationship in a representative area of the Loess Plateau over the period of 1960–2010 and found a continuous mild increasing trend of exponent b in an earlier period, but a much more significant increasing trend in a later period. It was notable that an increase in the exponent b and a decrease in log $\hat{a}$ accompanied ecological restoration over the past 51 years, and that the new discharge–sediment relationship implied that a low discharge leads to lower sediment and a high discharge leads to higher sediment—indicating a potential risk of a large sediment load during extremely wet years. In other words, a relatively high sediment load is still likely, despite the usual low sediment load. Therefore, managers of watersheds and downstream reservoirs should pay much more attention to extreme rainfalls and be well prepared to mitigate potential damage to river/reservoir systems. In addition, channel erosion may be intensified under extreme rainfall due to the increased sediment starving that results from the changed discharge–sediment relationship. Overall, the present study and its outcomes are informative and valuable because they provide watershed managers with an alert: The current reduction or low level of discharge and sediment of the Loess Plateau may not necessarily be a new normal.

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Compliance with ethics guidelines

Pengcheng Sun, Yiping Wu, Zhifeng Yang, Bellie Sivakumar, Linjing Qiu, Shuguang Liu, and Yanpeng Cai declare that they have no conflict of interest or financial conflicts to disclose.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2019.07.014.

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