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# Response of sediment yield to vegetation restoration at a large spatial scale in the Loess Plateau

LIU XiaoYan[1*], YANG ShengTian[2], DANG SuZhen[3], LUO Ya[2], LI XiaoYu[4] & ZHOU Xu[2]

[1] *Yellow River Conservancy Commission, Zhengzhou 450003, China;*
[2] *School of Geography, Beijing Normal University, Beijing 100875, China;*
[3] *Yellow River Institute of Hydraulic Research, Yellow River Conservancy Commission, Zhengzhou 450003, China;*
[4] *Yellow River Institute of Hydrology and Water Resources, Zhengzhou 450004, China*

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The impact of vegetation coverage on erosion and sediment yield in the Loess Plateau has been extensively studied, but the research has been primarily based on observations from slope runoff plots or secondary forest regions; the scaling method remains unresolved when it is applied at a large spatial scale, and it is difficult to apply to regions with severe soil and water loss given the predominance of herbs and shrubs. To date, there is little data on the quantitative impact of changes to vegetation on sediment concentration at a large spatial scale. This paper is based on vegetation information from remote sensing images, measured rainfall and sediment data over nearly 60 years, and results from previous runoff and sediment variation research on the Yellow River. We introduce the concepts of a sediment yield coefficient and the percentage of effective vegetation and erodible area, analyze the impact of different vegetation conditions on the flood sediment concentration and sediment yield, and evaluate the effect of rainfall intensity on sediment yield under different vegetation conditions at the watershed scale. We propose models to evaluate the impact of vegetation on sediment yield in the loess gully hilly region, which are based on remote sensing data and support an application at a large spatial scale. The models can be used to assess sediment reduction that results from the current significant improvement of vegetation in the Loess Plateau.

**Loess Plateau, large spatial scale, forest and grass vegetation, sediment concentration, sediment yield**

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## 1 Background

Since 2000, the vegetation restoration has been significant in the Loess Plateau, most prominently in the region from Hekouzhen to Longmen and in the upper and middle reaches of Beiluohe River. Almost concurrently, the measured sediment discharge of the main stem of the Yellow River has been significantly reduced, and the incoming sediment at Tongguan station has been reduced by 82% from 2000 to 2013. In this context, the quantitative relationship between vegetation level and sediment reduction at a large spatial scale has become increasingly important.

The relationship between vegetation and sediment yield in the Loess Plateau has in fact been an important research subject for decades. Since the 1950s, Hou and Wang studied the relationship of vegetation coverage and sediment yield, respectively, by regression analysis [1–3]. Hou suggested that the effective forest coverage for soil and water conservation was more than 60%, and that ground vegetation and litter played a significant role in reducing sediment yield [2]. Wu found out that the runoff of pinus tabulaeformis forest with withered litters was just 1/6 that of pinus tabulaeformis forest without withered litters, and the sediment load was

*Corresponding author (email: liuxiaoyan@yrcc.gov.cn)

just 3.5% of the latter [4]. Romero revealed that plant cover was a key factor influencing the suspended sediment concentration, total sediment yield and proportion of different types of sediment [5]. Based on the results of these and other studies, Tang, Meng and Jing suggested that the major factors contributing to the effect of vegetation on sediment reduction were vegetation coverage, the thickness of litter layer and the plant roots; surface erosion was extremely weak when vegetation coverage was greater than 70% [6–9]. Although these results reveal the impact of vegetation on the erosion mechanism, they are primarily based on observations of runoff plots or secondary forest regions. The proposed model derived from runoff plot failed when it was applied to the watersheds and basin [10], or to severe soil erosion areas dominated by herbaceous and shrub vegetation.

In order to evaluate the impact of vegetation improvements on sediment reduction on a large spatial scale, the equation of area of vegetation * local erosion modulus * reduction factor was commonly used [11–13]. The main problem of this method is that the statistical forest and grass area is artificial and much more smaller than the actual size of native forest and grassland, and there is no information of real forest and grass coverage, so the calculation results should be discounted, while the determination of discount coefficient tend to have certain subjectivity. An additional shortcoming of this approach is that it is not just the vegetation area itself that reduces sediment yield, but also reductions in slope-to-valley runoff, a factor that has not been included in previous methods.

For the water sediment concentration research in the Loess Plateau, Xu analyzed the relationship between sediment concentration and land surface composition [14], Wang studied the generation and confluence of hyperconcentrated flow in the gully and hilly regions of the Loess Plateau [15], Liao found that hyperconcentrated flow occurs basically within an area with annual precipitation of 200–600 mm and a range in NDVI value of 0.115 to 0.125 [16]. There have been, however, few reports on the quantitative impact of vegetation change on sediment concentration at a large spatial scale.

In order to provide an objective evaluation of the impact of vegetation on sediment reduction at a large spatial scale, this paper analyzes measured precipitation and sediment data in the gully and hilly area of the Loess Plateau from 1966 to 2012, extracting land use and vegetation coverage information for 1978, 1998, 2010 and 2013 based on remote sensing images, establishing the quantitative relationship between the sediment yield coefficient and the percentage of effective vegetation in the Loess Plateau, and between flood sediment concentration and vegetation coverage.

## 2 Study area and data

### 2.1 Study area

This study focuses on the gully and hilly area of the Loess Plateau, where the sediment yield accounts for approximately 85% of the total sediment yield of the Yellow River. The data selection area is shown in Figure 1. Even though the selected area belongs to the gully and hilly area, the surface composition and slope are quite different. The surface soil of the Huangfuchuan River basin is for the most part composed of feldspathic sandstone, and is referred to as the feldspathic sandstone area in this paper; the upper and middle reaches of the Tuwei River basin, the middle reaches of Kuye River basin, and the upper reaches of Wuding River basin are largely a loess hilly-gully region with the surface covered by sand, hereinafter referred to as the sand-covered area; the surface materials of the other regions are loess, and referred to as the loess area. Overall, the loess area from Hekou to Longmen and the upper reaches of the Beiluo River and the Jinghe River have more broken terrain.

### 2.2 Precipitation and sediment yield data

The daily rainfall for each tributary from 1966 to 2012 was calculated using data from 305 selected rainfall stations. Because most rainfall does not result in runoff or sediment yield in the Loess Plateau [5], annual rainfall with daily rainfall of more than 10, 25 and 50 mm was counted for each hydrological station control area, expressed as $P_{10}$, $P_{25}$, $P_{50}$, respectively, with a unit measure of mm. The degree of rainfall concentration is represented by $P_{50}/P_{10}$.

All of the measured data derive from the sediment discharge, runoff in flood season and the measured annual maximum sediment concentration, which is expressed as $S_{\max}$ (kg/m$^3$), for each hydrological station in every tributary included in the study. Dividing the measured runoff from June to September by the sediment discharge over the same period, we can obtain the average sediment concentration in the flood season, which is expressed as $S_{\text{ave}}$ (kg/m$^3$).

Based on the measured sediment discharge, sediment production yield for the control region at each hydrological station is obtained by restoring the amount of the retained sediment by dams and the amount of sediment diverted by irrigation.

The sediment yield coefficient is introduced, which refers to the sediment yield per unit area for a unit of rainfall in the watershed on the plateau. The larger the value, the stronger the sediment yield capacity of a unit of rainfall, which is calculated as follows:

$$S_i = \frac{W_s}{A_e} \times \frac{1}{P}, \tag{1}$$

where $S_i$ (t/km$^2$ mm) represents the sediment yield coefficient; $W_s$ (t) represents the annual sediment yield of the watershed; $A_e$ (km$^2$) is the erodible area of the watershed, referring to the land area by removing riverbed, stone mountain area and construction land; $P$ (mm) is the rainfall amount.

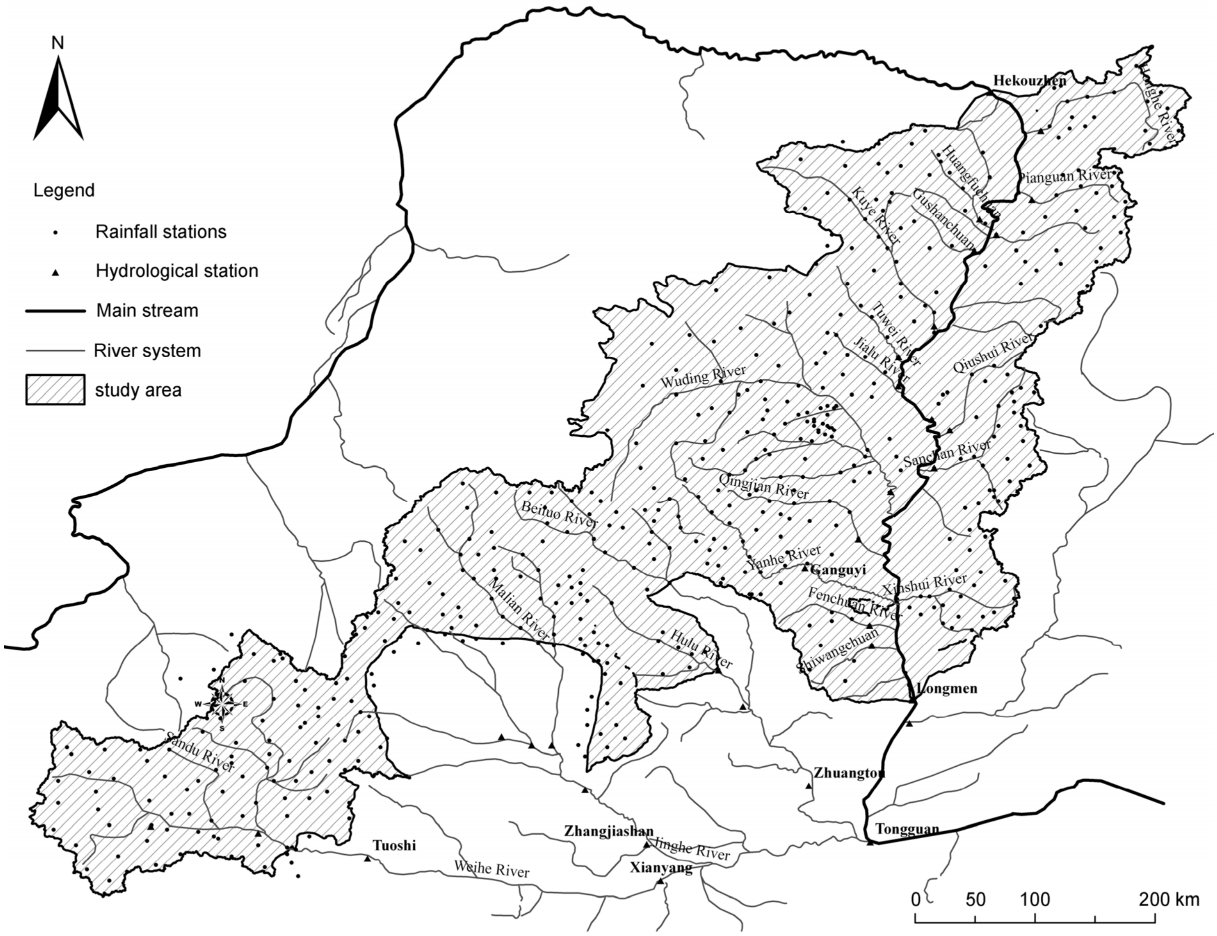


**Figure 1** Map of the study area.

### 2.3 Vegetation data

To determine whether vegetation has the effect on sediment reduction, it is necessary to know whether its and coverage have changed, compared to its original status. To do this, we defined the following related concepts based on satellite remote sensing information.

A forest and grassland area is defined as the total area of forest land, grassland and unused land in a watershed erodible area, represented by $A_v$. The concept of forest and grassland proportion is introduced to illustrate forest and grassland scale in different watersheds. It refers to the proportion of forest and grassland area of the erodible area in a watershed, represented by $A_v/A_e$.

Vegetation coverage is used to indicate the vegetation level in forest and grassland itself, represented by $V_c(\%)$, and refers to the proportion of projection area of leaves and stems in forest and grassland areas.

To reflect the and quality of forest and grassland comprehensively for each watershed, the concept of the percentage of effective vegetation is introduced, represented by $V_e(\%)$, which is the product of the proportion of forest and grassland and the vegetation coverage, and refers to the physical leaves and stems represented in an orthographically projected area within an erodible area in a watershed. The formula is as follows:

$$V_e = V_c \times \frac{A_v}{A_e}. \tag{2}$$

The erodible area, vegetation coverage, forest and grassland area should be extracted and calculated with remote sensing images to reflect the comprehensive effect of natural vegetation and artificial planting on the Loess Plateau. The vegetation data was extracted from remote sensing images in the summer or autumn of 1978(MSS), 1998(TM) and 2010(HJ), with spatial resolutions of 56, 30 and 30 m, respectively.

## 3 Sediment concentration in response to changes in vegetation

To highlight the impact of vegetation on sediment concentration, it was necessary to minimize the number of reservoirs, dams and terraces in the selected area. With the quantitative standard of that the control area proportion of dams and reservoirs is less than 10% of the erodible area and the terraced area is less than 4% of the erodible area, 18 tributaries and their secondary tributaries in the loess area were selected as the study area. The average $S_{\max}$ and $S_{\text{ave}}$ for each hydrological station from 1969 to 1989 and for some of the hydrological stations from 1994 to 2000 were calculated, and their relationship to vegetation coverage ($V_c$) in the same period is shown in Figure 2, respectively; the relationships can be expressed as

$$S_{\max} = 1245.4 - 9.28266 \times V_c, \quad (3)$$

$$S_{\text{ave}} = 604.95 - 6.3578 \times V_c. \quad (4)$$

There is a negative linear relationship between the flow sediment concentration and vegetation coverage of tributaries in the Loess Plateau; the correlation coefficient reaches 0.916 and 0.86, respectively. The relationship between sediment concentration and vegetation growth conditions can thus be demonstrated at a large spatial scale. Ground surface coverage, including forest, grass and crop vegetation, is clearly the key factor affecting erosion and sediment yield. The primary erodible land use types of the related tributaries in Figure 2, however, are slope land and forest and grassland from the 1960s to the 2000s, with very few terraces, and the planting structures in slope land are similar; the relationship shown in Figure 2 thus reflects the actual relationship between vegetation coverage and sediment concentration.

Figure 2 also shows that, even if the vegetation coverage reaches 60%–70% in the Loess Plateau, the maximum sediment concentration may still be up to 600 kg/m$^3$, and the average sediment concentration in the flood season may still be up to 200 kg/m$^3$, the most frequent type of flood of the tributaries in the Loess Plateau is still a hyperconcentrated flood. For example, the Yunyan and Shiwangchuan rivers originate in the secondary forest in Huanglong Mountain, and the vegetation coverage of the two tributaries was up to 80%–90% in the late 20th century, but their maximum sediment concentration for the corresponding period remained as high as 500–600 kg/m$^3$. The vegetation coverage of the Huangfuchuan, Jialu, Yanhe and Qingjian rivers was 46%,

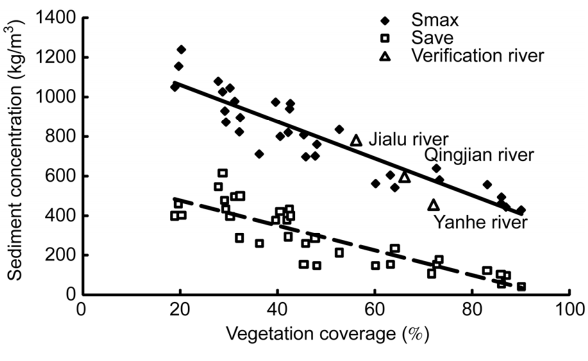


**Figure 2** Relationship between sediment concentration and vegetation coverage.

56%, 72% and 66% in 2013, respectively; although the annual sediment discharge was reduced dramatically in 2012 and 2013 as a result of heavy rain events, the maximum flood sediment concentration was still as high as 774, 784, 456 and 598 kg/m$^3$.

The influence of vegetation type on sediment concentration is not clear. In Figure 2, the points with vegetation coverage greater than 60% were extracted from the forest area, and others from the shrub and grass area. Even in 2013, the basin area of the Jialu, Yanhe and Qingjian rivers were covered primarily by shrub and grass, and Figure 2 shows that their data still follow the line trend.

## 4 Response of watershed sediment yield to vegetation change

Vegetation, soil and terrain are the key underlying surface factors affecting soil erosion. To understand the impact of vegetation change on sediment yield, there must be a minimal number of terraces during the data collection period. We determined that the terraced area should be less than 3% to 4% of the erodible area. Before the 1990s, the terrace scale of most tributaries was less than this; some areas still had very few terraces. The selected period of rainfall, runoff, sediment and vegetation data is mostly from the 1960s to 1990s, with very few periods after 2000; the average sediment yield coefficient and the percentage of effective vegetation were calculated for each of these periods, respectively. Because the sediment yield of the related tributaries in each period includes a sediment reduction effect for a small number of terraces, and the sediment reduction effect for level terraces is 90% or more [17–19], we then directly added the ratio of level terrace into the vegetation coverage for the related tributaries.

According to the composition of surface material and terrain and rainfall concentration degree, the percentage of effective vegetation and the sediment yield coefficient for each region are plotted in Figure 3. $P_{25}$ is used to calculate the sediment yield coefficient. Loess area 1 includes the Gushanchuan, Kuye and Jialu rivers as well as other rivers located in the northwest of region from Hekou to Longmen. The surface of loess area 1 is covered partly by sand, and $P_{50}/P_{10}$ can reach 18%–22%. Loess area 2 includes the middle and lower reaches of the Wuding, Qingjian, Yanhe, and Qiushui rivers and the upper reaches of the Beiluo River, where nearly 50% of the erodible area has a slope larger than 25 degrees, and $P_{50}/P_{10}$ is between 12% and 17%. Loess area 3 includes the eastern and southern parts of the region, from Hekouzhen to Longmen, and the upper reaches of the Jinghe River, where 30%–40% of the erodible area has a slope larger than 25 degrees, and $P_{50}/P_{10}$ is between 10% and 18%. Loess area 4 includes the upper reaches of the Weihe, Pianguan and Hunhe rivers, where 16%–21% of the erodible area has a slope larger than 25 degrees, and

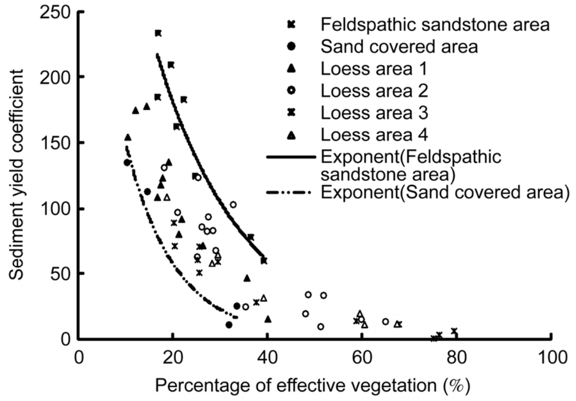


**Figure 3** Influence of vegetation change on watershed sediment yield.

$P_{50}/P_{10}$ is between 7% and 10%.

As shown in Figure 3, the relationship between $S_i$ and $V_e$ of the tributaries generally follows the same trend, and all are exponentially correlated. Although the relationship between $S_i$ and $V_e$ of the feldspathic sandstone area and the sand covered area has the same trend as that in the loess area, the points are clearly on the top or bottom; in other words, the sediment yield is larger or smaller than that in the loess area under the same vegetation conditions. Although the terrain and rainfall concentration degree are significantly different in the four loess areas, the $S_i-V_e$ relationship has no clear difference. The curves of the feldspathic sandstone, sand covered and loess areas can be expressed by eqs. (5)–(7). The correlation coefficients are all larger than 0.93, which is a good representation of the relationship between vegetation condition and sediment yield at a large spatial scale.

$$S_{fi} = 545.48\times e^{-0.0549\times V_e}, \tag{5}$$

$$S_{si} = 343.81\times e^{-0.0578\times V_e}, \tag{6}$$

$$S_{li} = 347.62\times e^{-0.058\times V_e}. \tag{7}$$

As shown in Figure 3, vegetation improvement has a significant sediment reduction effect when the percentage of effective vegetation is smaller than 40%; the range of sediment reduction due to vegetation improvement slows down when the percentage of effective vegetation ranges from 40% to 60%; when the percentage of effective vegetation is larger than 70%, the sediment yield coefficient tends to be stable, and sediment yield can be contained in the watershed for the most part.

The relationship between vegetation and sediment yield shown in Figure 3 is qualitatively consistent with the research results of Tang et al. [6,20,21]. Based on 11 sets of sediment transport moduli and forest coverage data for the surrounding tributaries in Ziwuling, Tang plotted their relationship; based on six groups of observations of runoff plot in the Huangfuchuan River basin, Jing established the relationship between erosion moduli and grass coverage; with the use of watershed sediment discharge data and vegetation coverage obtained from TM images, Lu plotted the relationship between vegetation coverage (including farmland vegetation) and sediment discharge for different types of geomorphic regions in the middle reaches of the Yellow River. We introduce the concept of the sediment yield coefficient, however, which restores sediment yield by dams, and strictly controls the terrace scale. Our data collection is limited in the gully and hilly area of Loess Plateau; the percentage of effective vegetation excludes the vegetation on farmland and construction land. It therefore highlights the relationship between sediment yield and vegetation conditions in the soil erosion area, and can be used in a coarse sandy area with primarily herbs and shrubs.

Based on the observed data from the sloping runoff plots, the influence of terrain on erosion yield is considered to be very complex: sediment yield increases with an increase in slope when the surface slope is less than 24 degrees; slope erosion peaks when the slope is between 24 and 29 degrees; after that, slope erosion quantity begins to decrease. In a watershed, land surface is in fact characterized by multiple gradients of slope scale, so it is understandable that the relationships between $S_i$ and $V_e$ are not clearly different in the loess areas, even though there are large differences between terrain and rainfall concentration degree, as reflected in Figure 4. In other words, at the watershed scale, natural terrain has little effects on sediment yield in the hilly-gully loess region where there are very few terraces.

Figure 3 shows that besides vegetation, surface composition is also an important factor influencing watershed sediment yield. However, because vegetation improvement can significantly reduce watershed flood discharge (the flood yield coefficient in Figure 4 refers to the flood yield by unit rainfall in per unit area), it has a greater impact on the total sediment yield of a watershed; even more important, the surface soil structure cannot be changed on a large scale, but vegetation coverage can be improved over a wide area.

In the second half of the 20th century, the proportion of effective vegetation in the sandy area of the Loess Plateau

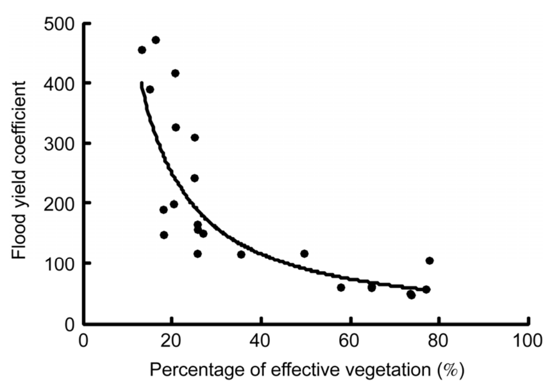


**Figure 4** Influence of vegetation change on watershed flood yield.

ranged from 12% to 27%. With the return of farmland to forest or grass, the percentage of effective vegetation in many parts of the serious erosion area in the region from Hekouzhen to Longmen and the Beiluo River basin reached 40% to 60% by 2013, so a sensitive period of vegetation change and sediment yield response has recently been experienced.

## 5 Impact of rainfall intensity on sediment reduction ability of vegetation

$P_{25}$ is used to calculate the sediment yield coefficient in Figure 3. In order to find a more sensitive rainfall factor to sediment production, rainfall indexes of $P_{10}$, $P_{25}$, $P_{50}$ were selected, and the relationships between sediment yield coefficient and percentage of effective vegetation are plotted in Figure 5. The figure shows that the square value of the correlation coefficient of the curves corresponding to $P_{10}$, $P_{25}$, $P_{50}$ is 0.8516, 0.8625 and 0.8372, respectively. This phenomenon is consistent with practical sediment yield from heavy rain across the Loess Plateau. According to the measured data from 1966 to 1980, the sediment yield from heavy rain in the northwest of the region from Hekouzhen to Longmen accounts for 50% to 80% of annual total sediment yield, but the sediment yield from heavy rain in other regions, shown in Figure 1, is just 30% to 50% of the annual total sediment yield. In view of this, $P_{25}$ or $P_{10}$ is recommended for the calculation of the sediment coefficient when measuring a sediment reduction amount from vegetation at a river basin scale.

The degree of average rainfall concentration ($P_{50}/P_{10}$) in Figure 3 and 5 is close to the average value for the period from 1966 to 2012. To understand the impact of rainfall intensity on sediment yield at different percentages of effective vegetation, the years in which the value of $P_{50}/P_{10}$ was equal to twice the mean value for other years were chosen, and the sediment yield coefficients and percentage of effective vegetation were then plotted, as shown in Figure 6.

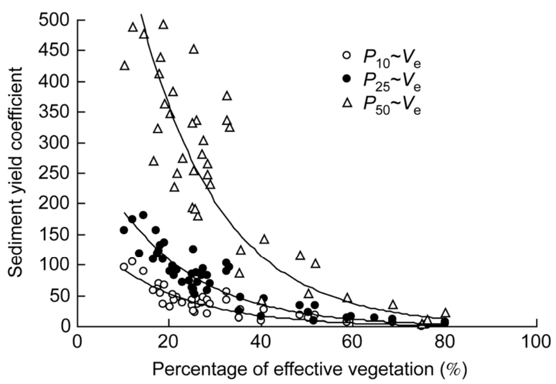


**Figure 5** Relationship between the percentage of effective vegetation and sediment yield coefficient of different rainfall indexes.

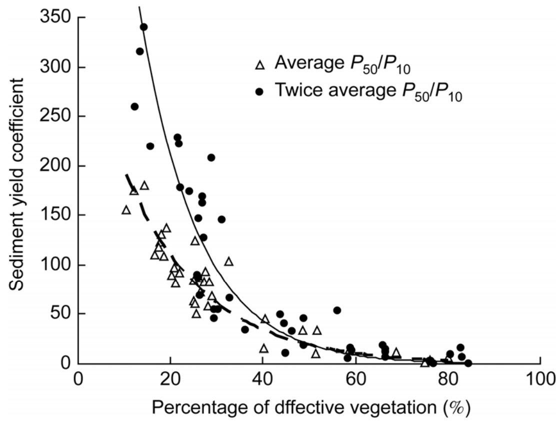


**Figure 6** Relationship between the percentage of effective vegetation and sediment yield coefficient of different rainfall intensity levels.

When the percentage of effective vegetation is less than 40%–45%, the sediment yield coefficient increases substantially with an increase in rainfall intensity; when the percentage of effective vegetation is greater than 50%, the sediment yield coefficients are not sensitive to rainfall intensity changes.

The results for typical tributaries also show that rainfall and its duration have a clearer effect on sediment yield than rainfall intensity for the tributaries with high vegetation coverage. From the 1970s to the 1990s, the percentage of effective vegetation of the Yunyan River and Heshuichuan was generally stable at 66% and 58%. Even in years when the value of $P_{50}/P_{10}$ was much larger than the average value for other years, the measured sediment yield was almost unrelated to the rainfall concentration degree (Figure 7). The data in Table 1 indicate that, in the case of similar $P_{25}$, sediment yield is not prominent at a higher rainfall concentration degree.

## 6 Conclusions

1) We analyzed the sediment concentration and sediment yield for different vegetation conditions at the watershed scale, and obtained high correlations using eqs. (3)–(7), which can be used to evaluate quantitatively the sediment reduction effect of vegetation improvements at a large spatial scale in the Loess Plateau.

2) There is a negative linear relationship between flood sediment concentration and vegetation coverage; that is, sediment concentration decreases with increasing vegetation coverage. Even if the vegetation coverage reaches 60%–70% in the Loess Plateau, the maximum flood sediment concentration may still reach 600 kg/m$^3$.

3) The sediment yield coefficient has an exponential relation to the percentage of effective vegetation at the watershed scale. When the percentage of effective vegetation is less than 40%, vegetation improvement has a significant

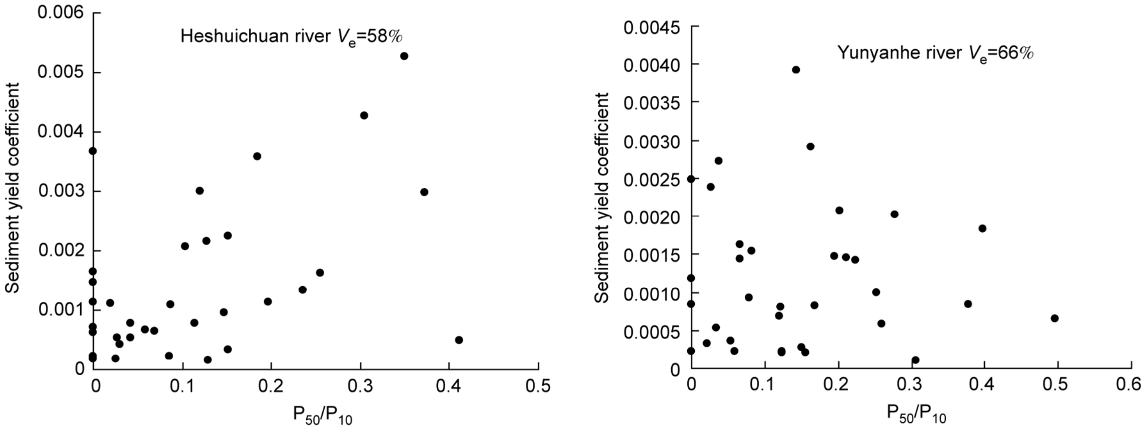


**Figure 7** Influence of rainfall intensity on sediment yield of typical tributaries.

**Table 1** Influence of rainfall intensity on sediment yield of typical tributaries

| Tributary name | Year | $P_{25}$ | $P_{50}$ | $P_{100}$ | $P_{50}/P_{10}$ | Sediment yield ($10^4$t) |
|---|---|---|---|---|---|---|
| Heshuichuan | 1975 | 181.8 | 115.6 | 68.1 | 0.256 | 232 |
| $V_e$=58% | 1996 | 178.9 | 59.8 | 0 | 0.152 | 316 |
| | 1990 | 181.5 | 46.4 | 4.63 | 0.043 | 150 |
| | 1991 | 173.1 | 60.3 | 0 | 0.185 | 490 |
| Yunyan River | 1978 | 222.5 | 100.4 | 0 | 0.260 | 207 |
| $V_e$=66% | 1988 | 234 | 58.9 | 0 | 0.143 | 1453 |
| The upper reach of Yunyan River | 1978 | 233.3 | 110.2 | 0 | 0.281 | 59 |
| $V_e$=76% | 1969 | 248.1 | 36.5 | 0 | 0.083 | 45 |

impact on reducing sediment; when the percentage of effective vegetation is greater than 70%, the sediment yield coefficient tends to be stable.

4) Despite the fact that vegetation, soil and terrain are all the important underlying surface factors affecting erosion and sediment yield in the Loess Plateau, if there is no terrace, the impact of terrain difference is not clear at the watershed scale in the loess gully and hilly region; surface composition has a significant influence on sediment yield, but is not possible to change over a wide area.

5) The sediment yield coefficient increases with an increase in rainfall intensity when the percentage of effective vegetation is less than 40%–45%; when the percentage of effective vegetation is greater than 50%, however, the sediment yield coefficient is not sensitive to a change in rainfall intensity.

6) The application of the proposed model should be based on a reasonable understanding of the original condition of vegetation in the tributaries. Most of the sandy area in the Loess Plateau experienced a period of both destruction and restoration in the 20th century. Vegetation surrounding the natural forest still suffered destruction even in the mid 1990s. It is therefore important to determine a proper natural period to objectively evaluate the impact of vegetation improvements on reducing sediment.

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