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RESEARCH PAPER

# Effect of vegetation on runoff-sediment yield relationship at different spatial scales in hilly areas of the Loess Plateau, North China

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**Abstract:** Whether vegetation reduces soil loss by reducing runoff volume or rather by changing runoff-sediment yield relationship has received little attention. Base on the observed data from monitoring stations and the published data from other research, this issue is addressed at different scales in hilly areas of the Loess Plateau, North China. At the plot scale, vegetation helps reduce soil loss not only by reducing runoff volume, but also by changing the runoff-sediment yield relationship, resulting that the sediment-reduction rate is higher than the runoff-reduction rate. At the watershed scale, gully erosion and mass wasting process are dominant. Vegetation measures are insufficient to control local mass movement, implying that sediment availability remains high even after vegetation is established. It is also hard for slope vegetation to change the capacity of the sediment transport system at the watershed scale. Therefore, vegetation cannot change the runoff-sediment yield relationship at the watershed scale. This implies that vegetation reduces sediment yield only by reducing runoff volume and the sediment-reduction rate approximates the runoff-reduction rate at the watershed scale. Other slope measures for soil conservation such as terraces are considered to have the same effect on the runoff-sediment yield relationship as the vegetation. Several case studies involving different spatial scales are presented and confirm this conclusion.

**Key Words:** runoff-sediment yield relationship; scale; vegetation; slope measure; land use/land coverage; hilly loess areas

Fluvial processes are typically scale-dependent[1]. The dominant erosion and sediment processes and the driving force vary with scales, thereby leading to different laws of soil erosion and sediment yield at different scales[2]. Hence, how the water and soil conservation measures work and what their beneficial effects on erosion control are may also vary with spatial scales. Numerous studies have reported the vegetation influence on soil erosion. However, many of these studies were carried out at the hillslope or experiment plot scale. Increases in spatial scales involve increases in landscape complexity and heterogeneity, new variables and new processes. Then a direct extrapolation of the results obtained at plot scales to larger spatial scales is expected to be extremely difficult. For example, some studies reported that as a result of land use or climate change, erosion rate declines in upslope areas, but no significant changes are observed in total sediment discharge at the watershed outlet[3–5]. The effect of vegetation on erosion and sediment processes varies with spatial scales[6], and hence vegetation or other soil conservation measures which have the greatest benefit to soil conservation at the plot or hillslope scale may not remain the same benefit at the watershed scale. On the other hand, the work mechanism of vegetation on soil conservation, that is, whether vegetation reduces soil loss by reducing runoff volume or rather by changing runoff-sediment yield relationship, is not known exactly, especially at the watershed scale. The objective of the present paper is to reveal effects of vegetation on runoff-sediment yield relationship at different spatial scales in hilly areas of the Loess Plateau, North China. Accordingly, we present runoff and sediment yield data involving four scales:

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plot, entire slope (including both inter-gully and gully slopes), small watershed and large watershed. Based on these data and the runoff-sediment yield model proposed by Zheng[7], how vegetation reduces soil loss or sediment yield at these four different spatial scales is discussed.

## 1 Outline of study area and data sources

The Loess Plateau in North China, located in the middle Yellow River basin (Fig. 1a), is among the regions with the highest erosion intensity in the world[8]. The 236 000 $km^2$ hilly loess areas, where the mean annual rate of soil loss exceeds 10 000 t $km^{-2}$ [9], is one of the most severely eroded regions of the Loess Plateau[10]. This region is covered by a thick loess mantle with an average depth of more than 100 m[10]. Late Pleistocene loess, or Malan Loess, is dominant. It is silty in texture and weakly resistant to erosion. The climate is generally semi-arid and temperate with approximately two-thirds of the annual precipitation occurring as short-duration and high-intensity storms[10]. One of the reasons for intensive soil loss in this region is hyperconcentrated flow, which has very strong erosion and transport capabilities[8]. Hyperconcentrated flow has been widely observed in the middle Yellow River basin[8] and sediment concentrations in a runoff of over 1000 $kgm^{-3}$ have been recorded regularly[11].

Suffering from intensive water erosion, hilly loess areas have been dissected into numerous small watersheds where similar soil properties, topography features and erosion and sediment processes have appeared[12]. The 9.1 $km^2$ Wangjiagou watershed (Fig. 1b), located about 4 km north of Lishi County (111°09′E, 37°33′N), is typical of these small watersheds[13]. Its elevation ranges from 1000 m to 1320 m. The annual average precipitation is 505.7 mm with about 80.6% falling between May and September, and the runoff only occurs as a result of rainfall. The surface soil (Malan Loess) mainly consists of thick silty loess. The Tertiary red clayey earth is widely exposed at the lower slope section. The watershed is highly dissected by a dense drainage network with a mean drainage density of 7.01 km/$km^2$. The gully area in Wangjiagou watershed occupies 44% and the inter-gully area occupies 56%. The native vegetation disappeared several hundred years ago[14], and most of the cropland is now cultivated with maize or millet.

With the aim of collecting data for the study on erosion and sediment yield, some experiment stations have been established in the middle Yellow River basin, among which data from the Wangjiagou experimental watershed is relatively complete[14]. The data[15] were printed for internal use. All measurements of discharge, concentration, grain size and load of suspended sediment follow national standards issued by the Ministry of Water Resources and Electric Power of China[16,17]; the measurement procedures are basically the same as those used internationally. For the details of the procedures, see Yan[18] and Sedimentation Commission of Chinese Society of Hydraulic Engineering[19]. Strict checks were carried out to comply with the standards; consequently, as Xu [14], we considered the accuracy of the data to be reliable. It should be noted that according to Mou and Meng[20], the strong sediment-carrying capacity of hyperconcentrated flows and fine sediment load in this region means that almost all of the sediment (>95%) in motion can be regarded as wash load[8]. Hence, bedload can be ignored and the measured suspended sediment load can be regarded as the total load. Additional information on data collection and the Loess Plateau can be found in[14] and[7].

Unless otherwise stated, all of the data used in this study are derived from the Wangjiagou experimental watershed. The

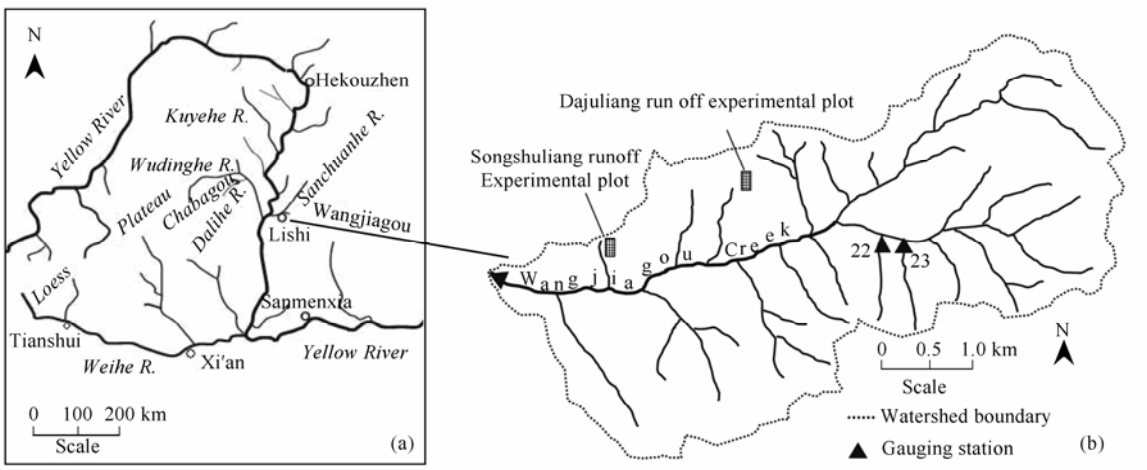


Fig. 1 Location of the study area

(a) Middle Yellow River basin, modified from [14]; (b) Wangjiagou Creek, modified from [7]

The numbers on map (b) refer to the numbers in Table 1. Number '22' represents Yangdaogou subwatershed and number '23' represents Chacaizhugou sub-

Yangdaogou (non-managed) and Chacaizhugou (managed) experimental subwatersheds (#22 and #23 in Fig. 1b) are adjacent to each other in the upper part of Wangjiagou Creek. They were established in order to assess the beneficial effect of soil conservation measures, especially those on slopes. A 15-year observation of them was made and the data are used in the present study at the small watershed scale. Their main characteristics and a summary of the observed data are shown in Table 1. Detailed information about these two subwatersheds will be given below. A number of runoff experiment plots were also established in Wangjiagou watershed in order to assess such factors as vegetation, slope gradient and slope length on soil erosion. Among these runoff experiment plots, the Dajuliang and Songshuliang experiment plots (Fig. 1b) were selected for the study at the plot scale owing to their similar plot characteristics (Table 2). In addition, the data from an entire slope plot including both inter-gully and gully slopes (see Fig. 2) in Yangdaogou subwatershed were used for the study at the entire slope scale. An overview is given in Table 2 about the observed data and plot properties for these three plots.

As in other small watersheds in hilly loess areas, the gully edge, where a sharp break in slope gradients appears, separates the hillslope into two parts: the gully area and the inter-gully area (Fig. 2). The inter-gully area is also termed as inter-gully hillslope in Chinese literatures, which can be further subdivided into three zones: hilltop, upper hillslope and lower hillslope. The gully area is composed of two zones: gully slope and channel. It is noticed that the combination of inter-gully hillslope and gully slope is termed as the entire slope in Chinese literatures. In hilly loess areas, most parts of the inter-gully area are arable land; the gully slope is too steep to be cultivated and the dominant land use is grazing by sheep and goats. As shown in Fig. 2, the slope steepness increases downslope from 0–5° to 30–45°, accompanied with a gradual change in the dominant erosion process. Hilltops are dominated by raindrop splash and sheet erosion, and upper hillslopes by rill erosion. Master rills appear on lower hillslopes. On gully slopes, there exist bank gullies (see Fig. 5), through which most of the runoff and sediment run into the gully channel[21]. Mass wasting processes such as sliding and collapsing, normally with low magnitude, are active at bank gully walls. These mass-wasted materials cannot stay at the bottom of bank gullies for a long time[22] and are generally flushed up by one or two high-intensity storm events or within one or two

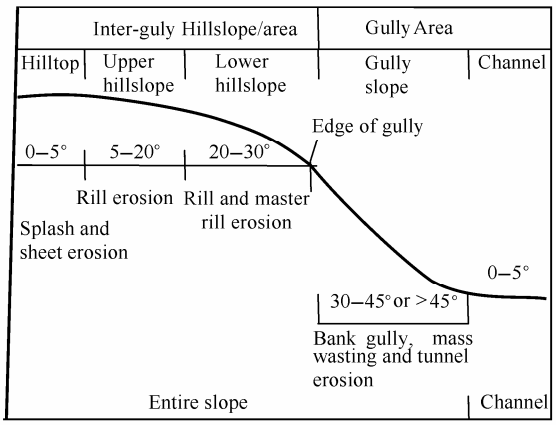


Fig. 2 Sketch map showing topography features and erosion processes along the flow path in the study area (modified from [13])

Table 1 Observed data and watershed properties for Yangdaogou and Chacaizhugou subwatersheds

| Experimental subwatershed | Observation period | Number of recorded events | Monitoring equipment | Area ($km^2$) | Length of main gully (m) | Watershed width (m) | Average slope (%) | Percentage of different slope groups (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 0–15° | 16–30° | >30° |
| Chacaizhugou (#23 in Fig. 1b) | 1956–1970 | 89 | Partial flume | 0.193 | 776 | 249 | 11.9 | 19.4 | 46.1 | 31.8 |
| Yangdaogou (#22 in Fig. 1b) | 1956–1970 | 114 | Partial flume | 0.206 | 752 | 274 | 12.6 | 17.83 | 39.77 | 42.4 |

Table 2 Experiment plot properties and their observed data

| Site | Plot type | Land type | Slope gradient | Slope aspect | Slope length (m) | Soil type | Area ($m^2$) | Observation period | Monitoring equipment |
|---|---|---|---|---|---|---|---|---|---|
| Songshuliang | Plot at inter-gully area | Farmland | 30° | NE | 20 | loess | 200 | 1957–1958 | Water collection tank |
| Dajuliang | Plot at inter-gully area | Locust forest | 31° | NE | 23.1 | loess | 200 | 1957–1959<br>1963–1964 | Water collection tank |
| Yangdaogou | Entire slope | Farmland at upper slopes and waste land at lower slopes | | NE | 185 | loess | 4167 | 1963–1968 | Partial flume |

years[23]. For higher-order gullies, besides sliding and collapsing, other mass wasting processes such as landsliding and earth-debris flowing are also active and often produce a large quantity of debris materials that need a long time to be carried away[22]. Mass wasting is one of the important processes affecting the sediment yield in Loess Plateau[22]. Mass-wasted materials are dominated by silt fractions and thereby very suitable to be transported by flowing water. In addition, the hyperconcentrated flows have extremely high transport capacity. Hence, a strong coupling relation exists between hyperconcentrated flows and gravitational erosion, which allows a rapid removal of mass-wasted materials. This coupling relation can be regarded as the most important factor responsible for the high-intensity erosion and sediment yield in the middle Yellow River basin[8].

## 2 Results and discussion

### 2.1 Modeling the runoff-sediment yield relationship using proportional function

In hilly loess areas, a general flow-sediment yield relationship can be observed across a wide range of spatial scales[9,12]: sediment concentration varies greatly when water discharge is below a critical value, whereas sediment concentration varies little and tends to be stable when water discharge exceeds this value. The relationship between flow discharge and sediment concentration can be considered as the flow-sediment relationship at the intra-event timescale. Likewise, the runoff-sediment yield relationship for different events can be considered as one kind of the flow-sediment relationship at the inter-event timescale. Zheng[7] found that the runoff-sediment yield relationship is determined by the flow discharge-sediment concentration relationship and there exists a strong similarity between the two flow-sediment relationships: the event mean sediment concentration varies greatly for small flood events (usually with the runoff depth of less than 1 mm); however, it varies little and tends to be stable for large flood events. Consequently, the relationship between runoff depth ($h$, mm) and area-specific sediment yield ($M$, t/km$^2$) for different events can be modeled using a proportional function: $M=Ch$, where $C$ is the regression coefficient.

Table 3 lists the regression results in the form of power, linear and proportional functions for Yangdaogou subwatershed, Chacaizhugou subwatershed and the entire slope plot. Except for the entire slope plot, the proportional function yields a determination coefficient higher than that of the power function and as much as that of the linear function. The observed data reveal that the relationship between water discharge and sediment concentration at the entire slope is also characterized by a stable sediment concentration when water discharge exceeds a certain critical value[21], and then the mean sediment concentration for large runoff events tends to be stable, as in the case of Yangdaogou and Chacaizhugou

Table 3 Regression results of runoff depth ($h$, mm) and sediment yield ($M$, t/km$^2$) for Yangdaogou, Chacaizhugou subwatersheds and the entire slope experiment plot

| Plot or monitoring station | Regression equation in the form: $Y=ax^b$ | | Regression equation in the form: $Y=ax+b$ | | Regression equation in the form: $Y=ax$ | |
|---|---|---|---|---|---|---|
| | Expression | $R^2$ | Expression | $R^2$ | Expression | $R^2$ |
| Yangdaogou | $M=195.7h^{1.49}$ | 0.833 | $M=621.83h-259.63$ | 0.961 | $M=611.03h$ | 0.959 |
| Chacaizhugou | $M=245.7h^{1.40}$ | 0.819 | $M=567.41h-116.15$ | 0.957 | $M=558.45h$ | 0.956 |
| Entire | $M=372.57h^{1.21}$ | 0.94 | $M=529.04h+80.68$ | 0.849 | $M=535.94h$ | 0.848 |

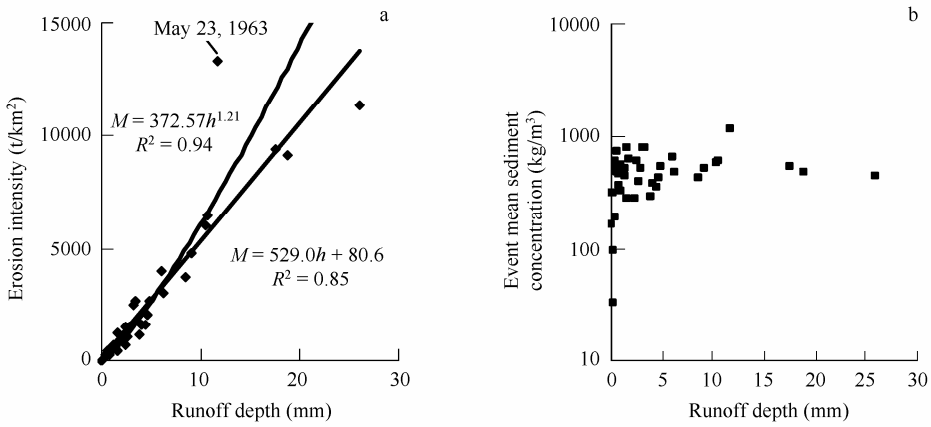


Fig. 3 Runoff-sediment yield relationship at entire slope scales

(a) runoff depth versus erosion intensity; (b) runoff depth versus event mean sediment concentration

subwatersheds (Figs. 3b and 6b). The power model yields a larger coefficient of determination than both linear and proportional models for the entire slope experiment plot; however, Fig. 3a reveals that the linear model performs much better than the power model, especially for large events, which is obviously due to the stability of the mean sediment concentration for high-magnitude events. The May 23, 1963 event (see Fig. 3a) was the first recorded event in that year, and recorded an exceptionally high mean sediment concentration probably owing to the 'preparation' of a large amount of loose materials on land surface prior to this event. If this event is removed out of the regression analysis, the proportional model yields a determination coefficient (0.9653) nearly as much as that of the linear model (0.9658) and higher than that of the power model (0.9391).

It should be noted that the *C* value in the proportional model represents the mean sediment yield per unit runoff during flood events or the mean sediment concentration for all events under consideration. In addition, in the loess areas, sediment supply is generally abundant without limit, and sediment flux is transport-limited. Thus, sediment concentration is directly related to the transport capacity of flows and then the *C* value also represents the mean sediment transport capacity per unit runoff during flood events. Especially, the *C* value can be representative of the stable sediment concentration when water discharge exceeds a critical value for a specific watershed[7]. The proportional model can produce reasonable results for high-magnitude events, especially for extreme events. Despite the poor model performance for low-magnitude high-frequency events, this model can be considered as a good reflection of the runoff-sediment yield relationship for different events in a specific watershed because of the heavy weight of large flood events in determining this relationship or mean sediment yield per unit runoff during flood events. Therefore, the change in the *C* value is considered equivalent to the change in the runoff-sediment yield relationship in the following section.

### 2.2 Experiment plot scale at the inter-gully area

Vegetation has been proved to be very effective in the erosion control. Vegetative canopy cover intercepts raindrops, reducing their impact energy on the soil surface. The surface litter shields the soil surface from direct raindrop impact and significantly enhances infiltration and decreases ground roughness[2]. In addition, plant roots can greatly enhance soil stability and anti-erodibility. Therefore, at the plot scale, vegetation reduces soil loss not only by reducing runoff volume, but also by changing the runoff-sediment yield relationship as a result of the decrease in both the erosion and transport capacity of the flow. Thus, the sediment-reduction rate is expected to be higher than the runoff-reduction rate at this scale. The data observed during the period of 1955–1988 in Wangjiagou watershed show that at the artificial forested and grassed plots, the runoff-reduction rates are 30.8% and 5.6%, respectively, and the sediment-reduction rates are 88.8% and 77.4%, respectively[24].

Songshuliang (vegetated) and Dajuliang (cultivated) plots were established at the inter-gully land. These two plots possess more or less the same size, slope gradient and aspect, and soil property (Table 2). However, the two plots exhibit substantially different runoff-sediment relationships (Fig. 4) owing to the effect of vegetation. With a considerable scatter of the data points, the vegetated plot exhibits an event mean sediment concentration much lower than that at the cultivated plot. In addition, at the vegetated plot, the event mean sediment concentration 7–8 years after trees are planted (1963–1964) decreases significantly compared with that 1–3 years after trees are planted (1957–1959), especially for high-magnitude rainfall events. Obviously, this observation is largely due to the improvement in the soil anti-erodibility at the experiment plot.

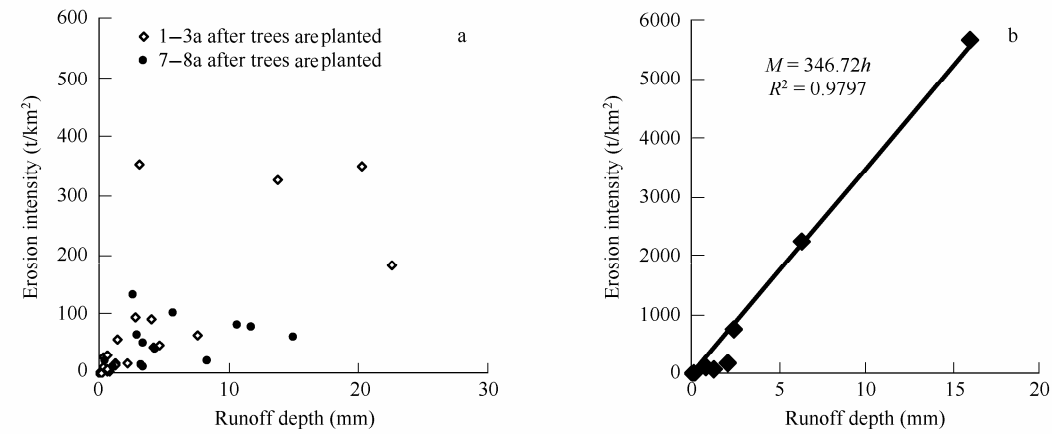


Fig. 4 Effects of vegetation on runoff-sediment yield relationship at experiment plots for (a) Dajuliang plot (vegetated); (b) Songshuliang plot (cultivated)

### 2.3 Entire hillsiope scale

As shown in Fig. 3b, for the entire slope at Yangdaogou subwatershed, the event mean sediment concentration (calculated by dividing the total sediment discharge by the total runoff discharge) varies little when the runoff depth exceeds 5 mm. An explanation for this observation is that the sediment deposition occurs when the sediment concentration of the flow from the lower hillslope exceeds the sediment transport capacity in the bank gully and otherwise, the flow scour occurs[21]. Since mass wasting processes occur frequently and provide sufficient loose materials, the sediment-transport capacity is expected to be always achieved at the outlet of the bank gully regardless of the value of the sediment concentration of the flow into the bank gully from the lower hillslope.

That vegetation practices change runoff-sediment yield relationship at the entire slope scale may be achieved in following two ways: 1) changing the sediment transport capacity by altering the particle size characteristics of sediment, or the landform outline in the bank gully, or the roughness at the bottom of the bank gully; 2) controlling mass wasting processes so that the flow cannot obtain sufficient sediment supply after it enters into the gully slope.

In Loess Plateau, vegetation measures can control sheet and rill erosion on slopes effectively; however, they are insufficient to control gully and gravitational erosion, especially on the loess areas where gullies cut deeply[8,25]. Thus, sediment supply also remains sufficient for flowing water after vegetation is established.

Since no particle size sorting follows mass wasting process, no variation is expected to occur in the particle size characteristics of sediment after vegetation is established. Vegetation can reduce soil loss induced by splash and sheet erosion. Furthermore, vegetation can also restrain the rill initiation and development by reducing runoff volume. Even, the master rill has a depth ranging from dozens of centimeters to 1–2 meters[26]. Plant roots are active in this depth so that they can serve as a dam resulting in water ponding and sediment deposition. This process, if going on again and again, a gentle micro-topography will appear at the master rill and consequently, the sediment transport capacity decreases. However, in Loss Plateau, the bank gully often has a depth varying from 1–2 meters to more than 10 meters and a width varying from several meters to dozens of meters[26]. In Wangjiagou watershed, the bank gully is often 10–30 meters wide and 5–20 meters deep[22]. In such a depth, the effect of slope vegetation is expected to be weak in enhancing soil stability and anti-erodibility. It is also almost impossible for slope vegetation to change the landform outline such as the slope gradient of the bank gully. In addition, it is actually very difficult to establish vegetation in the bank gully because of the poor soil moisture condition[27], the intensive scouring of the hyperconcentrated flow and the frequently occurring mass wasting processes. Consequently, the hydraulic roughness remains unchanged. Since the landform outline, the sediment property and the hydraulic roughness in the bank gully all remain unchanged after the slope vegetation is established, the sediment-transport capacity will also remain unchanged.

In general, vegetation can control the sheet, the rill and even the master rill erosion at the inter-gully hillslope, resulting in a decrease in the sediment concentration of the flow entering into the gully slope. However, sufficient loose materials derived from mass wasting processes are available for flowing water in the bank gully; thus, the flow will also achieve its sediment-transport capacity which remains unchanged after the slope vegetation is established. This implies that more sediment in bank gullies is expected to be entrained into water flow under the same flow event after vegetation is established. Consequently, after the slope vegetation is established, the same flow event (not the same rainfall event) is expected to yield less sediment at the inter-gully hillslope, more sediment at the gully slope and the same sediment at the entire slope. Hence, it can be concluded that vegetation practices can not change the runoff-sediment yield relationship at the entire slope scale.

### 2.4 Small watershed scale

#### 2.4.1 Yangdaogou and Chacaizhugou subwatersheds

Yangdaogou (non-managed) and Chacaizhugou (managed) subwatersheds (see Fig. 5) are neighboring one another and physically similar. As shown in Table.1, they have highly similar landform features. However, the Yangdaogou experimental subwatershed was intensively cultivated without conservation practices all the time during the monitoring period. The cultivated land occupies about 60% of the area. The vegetation coverage at the waste lands, most of which are too steep to be cultivated, is less than 30% as a result of intensive cattle grazing practices[28]. Before management practices were implemented, Chacaizhugou subwatershed had almost the same soil

Fig. 5 Photograph of bank gully, and Yangdaogou (non-managed) and Chacaizhugou (managed) subwatersheds

loss rate as Yangdaogou subwatershed. Since 1955, the soil conservation effort has been made. During the year of 1955, the relative managed area accounted for more than 50% and the vegetation coverage increased up to 75%[29]. At the end of the monitoring period, the relative managed area went up to 78.3%. Measures for the erosion control varied downslope. Bench terraces and field ridges were built at the upper hillslope; grass (mainly the sweet clover) was grown at the lower hillslope; as the soil moisture conditions in gullies favor tree growth, trees were selected both at gully slope and at gully channel, mainly including locust, willow and other relevant species. After several years' enclosure, the canopy density in the gully area has reached 0.6–0.8[30] and a thin litter has been developed in the forest[28]. In summer, the luxuriant forest and grass vegetation makes here cool and pleasant[30]. It should be noted that no engineering works such as check dams were installed within gully channels. During the 15-year monitoring period, the mean annual sediment yield at Yangdaogou is 20811 t/km$^2$, and 8503 t/km$^2$ at Chaicaizhugou; the mean annual runoff yield at Yangdaogaou is 36.7 mm and 16.2 mm at Chacaizhugou. Compared with Yangdaogou subwatershed, Chacaizhugou subwatershed saw its runoff volume decrease by 55.9% and sediment yield decrease by 59.1%. Since no gully engineering measures were constructed within Chacaizhugou subwatershed, these benefits can be considered to be achieved completely by vegetation and other slope measures.

Though a large scatter for the events with the runoff depth of less than 1 mm, Fig. 6[31] exhibits a perfect linear relationship between runoff volume and sediment yield for the events with the runoff depth of greater than 1 mm, which is obviously due to the stability of the mean sediment concentration for high-magnitude events. No significant difference is observed between the runoff-sediment yield relationships for managed and non-managed subwatersheds and this is entirely different from the case at the slope scale shown in Fig. 4. In Fig. 6a, the data points for the two subwatersheds intermix with each other. Their values of sediment yield per unit runoff over the monitoring period are therefore approximate each other (567 kg/m$^3$ for Yangdaogou and 524 kg/m$^3$ for Chacaizhugou). Also, their derived *C* values (Table 3) only show a slight difference. This difference can be largely attributed to the July 26, 1969 event (Fig. 6b) in Chacaizhugou. The high-magnitude events, especially the extreme events, exert the dominant influence on *C* values in the proportional model. The observed data show that the July 26, 1969 event, which produced the greatest runoff volume among the recorded events, has three flow peaks. Among them, the first and the second are accompanied with high sediment concentrations and the third, though recording the greatest flow discharge during this event, is accompanied with a rather low sediment concentration. This observation demonstrates that sediment supply was expected to be insufficient in the late period of this event owing to its massive sediment discharge. Thus, the sediment concentration at the third flow peak was far below the transport capacity of the flow. As a result, the observed hydrograph for the July 26, 1969 event, different from other events, is not characterized by a stable sediment concentration even if the flow discharge is large enough. The mean sediment concentration for this event (472 kg/m$^3$) is therefore rather low. After removing this event out of the regression analysis, the *C* value for Chacaizhugou is 607.38, which is almost the same as the *C* value for Yangdaogou (611.03).

To further verify the assertion above, namely, the derived *C* values for Yangdaogou and Chacaizhugou subwatersheds in Table 3 are statistically equal, one test procedure is designed. At first, one dependent variable *y* is established and it is defined as a combination of the recorded data of the area-specific sediment yield at the two experimental subwatersheds.

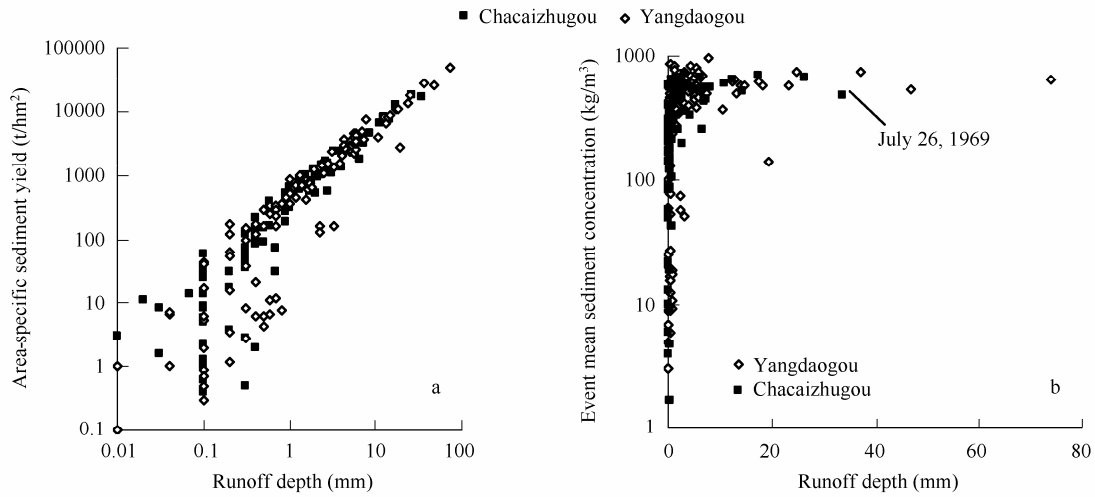


Fig. 6 Comparison of the runoff-sediment yield relationships of two studied watersheds

(a) runoff depth versus area-specific sediment yield; (b) runoff depth versus event mean sediment concentration

Then, two independent variables $x_1$ and $x_2$ are established. Like the dependent variable $y$, $x_1$ is the combination of the recorded data of the runoff depth at the two subwatersheds. $x_2$ is established as follows: to the sediment-yield records at Yangdaogou in $y$, the runoff-depth record for the corresponding events at Yangdaogou is assigned to $x_2$; however, to each of the sediment-yield records at Chacaizhugou in $y$, $x_2$ is set to zero. Thus, when the regression analysis is performed in the form of $y=ax_1+bx_2$, the a value is determined entirely by the data recorded at Chacaizhugou, and the b value is representative of the difference between the derived $C$ values for the two subwatersheds. If the same runoff-sediment relationship holds for the two subwatershed, then $b$ value is expected to be significantly equal to zero. At first, the test procedure is performed using all of the recorded events and the derived regression equation is $y=558.45x_1+52.58x_2$. Though the b value seems rather small relative to the a value, $T$-test result shows that we have to reject the null hypothesis of $b=0$ ($p=0.01$). However, after the July 26, 1969 event at Chacaizhugou is excluded, the derived regression equation is $y = 607.38x_1 + 3.65x_2$ and the $T$-test result shows that we can not reject the null hypothesis of $b=0$ ($p=0.88$). Hence, it can be concluded that the $C$ values for Yangdaogou and Chaicaizhugou subwatersheds in Table 3 are statistically equal and their runoff-sediment yields are therefore the same.

The creek gully has a larger size than the bank gully, and it is more difficult for vegetation practices to change its landform outline. However, there have been grass and trees growing in the gully channel at Chacaizhugou Creek. Obviously, this will exert significant influence on flow strength. In the loess regions of the middle Yellow River basin, hyperconcentrated flow can be formed by rain splash, and the successive processes of sheet, rill, gully and river channel erosion proceed under the influence of the hyperconcentrated flow[8]. Hyperconcentrated flow is a Binghamian flow rather than a Newtonian flow, and its physical properties and mechanical behavior are different from those of the normal flow[14]. The previous studies[8,25] reveal that vegetation measures can not effectively control the occurrence of hyperconcentrated flow. The observed data from several tributaries of the middle Yellow River demonstrate that hyperconcentrated flow can still occur even for the watershed with a forest coverage up to 50%.

If hyperconcentrated flow occurs, increased flow strength is not always required for further increase in sediment concentration; instead, sediment transport equilibrium can be maintained even under lower flow strength and higher sediment concentration[8,32]. In other words, low flow strength does not necessarily correspond to low transport capacity[14]. Thus, in loess areas, high sediment concentrations can be observed even when flow discharge is quite low in the later period of the flood event[12,14]. The fact mentioned above that the sediment concentration remains relatively constant when water discharge exceeds a critical value can also be interpreted as an indication that the decrease in the sediment transport capacity of the flow does not follow the decrease in flow strength. Although the vegetations in the gully channel increase the hydraulic roughness and thus reduce the flow strength, the flow strength is still expected to be in excess of the critical value. Consequently, no variation is observed in the sediment transport capacity of the flow after vegetation is established in the gully slope, even in the gully channel of Chacaizhugou Creek.

As mentioned before, vegetation measures cannot control the gravitational erosion effectively. As a result of the higher-magnitude mass-wasting events in the creek gully than in the bank gully, the sediment supply was expected to be also abundant after the management actions were taken in Chacaizhugou subwatershed. Owing to an unchanging channel transport capacity and consistently sufficient sediment supply, the same flow event will yield the same sediment discharge at the outlet of the Chacaizhugou subwatershed before and after its management practices start. This implies that vegetation and other slope conservation measures do not change the runoff-sediment yield relationship in Chacaizhugou subwatershed and they reduce the soil loss only by reducing runoff volume. The fact that the sediment-reduction rate (59.1%) approximates the runoff-reduction rate (55.9%) over the monitoring period confirms the assertion.

One event is selected randomly from the Chacaizhugou data set, and is compared with an event which records almost the same runoff volume in Yangdaogou subwatershed. It should be noted that the low-magnitude events are not considered in the selection process. The selected event in Chacaizhugou subwatershed occurred on July 15, 1962, recording a runoff depth of 12.2 mm, a flow peak of 1.34 $m^3/s$, an antecedent precipitation of 44.8 mm and an event mean sediment concentration of 650 $kg/m^3$; the event in Yangdaogou subwatershed occurred on August 14, 1962, recording a runoff depth of 12.3 mm, a flow peak of 3.447 $m^3/s$, an antecedent precipitation of 56.1 mm and an event mean sediment concentration of 619 $kg/m^3$. As shown in Fig. 7, during the heavy flow stage, the sediment concentration remains roughly stable at 650 $kg/m^3$ for the Yangdaogou event and at 750 $kg/m^3$ for the Chacaizhugou event. For most of the runoff, even at extremely low water discharge, the recorded sediment concentration achieves this stable value. Consequently, this stable value can be estimated as the event mean sediment concentration as mentioned in the preceding section.

The two selected events recorded approximately the same runoff volume and antecedent precipitation. Though the flow peak of the Yangdaogou event is nearly three times that of the Chacaizhugou event, the Chacaizhugou event has higher mean sediment concentration than the Yangdaogou event. Previously deposited sediment in the gully channel may be respon-

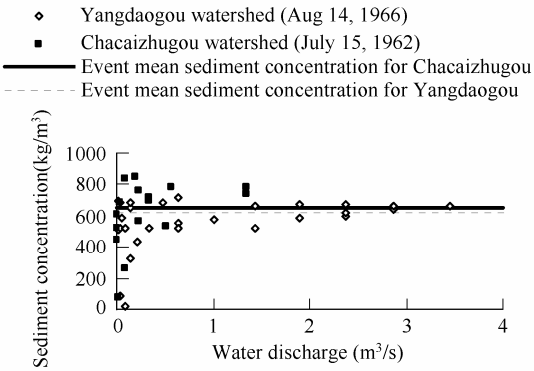


Fig. 7 Stable sediment concentration of two studied watersheds during two selected flow events

sible for this observation. The observed data in Chabagou watershed (Fig. 1a) in hilly loess areas reveal that all grain-size fractions of loess on a hillslope are eroded without sorting when the rainstorm intensity is sufficiently strong (> 0.3 mm $min^{-1}$)[12,14]. However, when the flow enters from the hillslope into the creek gully, if non-hyperconcentrated flow occurs, the coarse grains in suspended sediment may deposit owing to the decreasing slope; if hyperconcentrated flow occurs, the water flow is capable of entraining the previously deposited sediment on the gully channel, and thereby the suspended sediment grain size and sediment concentration increase[14]. Data analysis from Zhaoshiyao Hydrometric Station which is located in Wudinghe river basin (Fig. 1a) reveals a complicated relationship between sediment grain-size and sediment concentration[33]. With total sediment concentration increasing, the concentration of the < 0.01 mm fraction varies little; the concentration of the 0.05–0.1 mm fraction increases following a linear function; the concentration of the >0.1 mm fraction increases abruptly only at a total sediment concentration larger than 600 $kg/m^3$. This observation is largely responsible for the higher transport capacity of the flow in sandy loess belt than in clay and silty loess belts of Loess Plateau[34]. After >0.1 mm sediment goes into the flow, the sediment concentration increases rapidly; however, this fraction is relatively low in Wangjiagou watershed (silty loess). The local sediment transport capacity is therefore generally limited by the shortage of coarse sediment. However, previously deposited sediment, which was largely produced by small runoff events and is dominated by coarse fractions, can make a significant contribution to sediment discharge for following high-magnitude events[14]. Thus, it is expected that after quite a few small rainfall events, a large amount of coarse sediment is stored in the gully channel and an exceptionally high sediment concentration (transport capacity) is thereby observed during the following large flood event. Prior to the selected Chacaizhugou event, three low-magnitude flow events occurred with the runoff depths of 0.1 mm, 0.1 mm and 0.3 mm on July 2, July 12 and July 14, 1962, respectively. However, prior to the selected Yangdaogou event, one high-magnitude event with the runoff depth of 18.1 mm occurred on August 13, 1966. Thus, it can be inferred that a large amount of coarse sediment, especially >0.1 mm fractions of sediment, existed in the gully channel prior to the Chacaizhugou event and only a small amount prior to the Yangdaogou event. Consequently, a higher event mean sediment concentration was observed for the Chacaizhugou event than for the Yangdaogou event.

### 2.4.2 Qiaozidonggou and Qiaozixigou subwatersheds

Qiaozidonggou and Qiaozixigou experimental subwatersheds, located in the northern suburbs of Tianshui City (Fig. 1a), Gansu Province, China, are two neighboring subwatersheds in Jihe River basin. The annual average precipitation here is approximately 529.7 mm and all of the flow events occur in the flood season. The Qiaozidonggou subwatershed has a drainage area of 1.36 $km^2$ and a mean slope of 16.6%; the Qiaozixigou subwatershed has an area of 1.09 $km^2$ and a mean slope of 16.7%. Wheat and maize are the major crops grown in this area. Before 1985, sloping cultivated lands are dominant in both subwatersheds. Since 1985, the Qiaozidonggou subwatershed has experienced intensive soil conservation management practices. Conservation measures mainly include terraces and vegetated slopes. As in the Chacaizhugou subwatershed, no engineering works were constructed within gully channels. Up to 2001, sloping cultivated lands only accounted for 8.31% of the total area and terrace fields accounted for 43.12%[35]. Vegetations have been established on all the slopes which are prone to water erosion[36]. Compared with the year of 1985, the woodland has increased by 0.58 $km^2$ and the vegetation coverage has gone up to 44.43% in the Qiaozidonggou subwatershed[35]. Meanwhile, no management practices were implemented in the Qiaozixigou subwatershed. It was cultivated as before 1985 and vegetation is generally sparse[35].

The management practices in the Qiaozidonggou subwatershed brought great benefit to soil and water conservation. It was observed that eroded sediment was trapped in the forested and grassed slope, meaning a decreased sediment transport capacity of water flow. Compared with the non-managed Qiaozixigou subwatershed, the same rainfall event is accompanied with less runoff volume, less sediment discharge and lower peak flow at the outlet[37]. This observation reveals that the management practices in Qiaozidonggou subwatershed had reduced the runoff yield, in other words, changed the rainfall-runoff relationship. During the 17-year monitoring period, mean annual sediment yield at Qiaozidonggou is 3660 t and 7300 t at Qiaozixigou; mean annual runoff volume at Qiaozidonggou is 12000 $m^3$ and 21800 $m^3$ at Qiaozixigou[35]. The management practices in the Qiaozidonggou subwatershed reduce runoff volume and sediment yield by 44.9% and 49.8%, respectively. As in Yangdaogou and Chacaizhugou subwater-

sheds, runoff-reduction rate also approximates the sediment-reduction rate. Sediment yield per unit runoff is 305 kg/m$^3$ at Qiaozidonggou and 335 kg/m$^3$ at Qiaozixigou. Sediment yields per unit runoff are nearly the same in both managed and non-managed subwatersheds. This fact suggests that the sediment-transport capacity of the flow at the outlet of the Qiaozidonggou subwatershed, and also the runoff-sediment yield relationship remain unchanged after its management starts. The regression analysis involving the individual events observed from 1987 to 2004 confirms this. For the managed Qiaozidonggou subwatershed, the derived equation is[35]:

$$M=335.13h^{1.034} \quad (R^2=0.985) \tag{1}$$

And for the non-managed Qiaozixigou subwatershed, the derived equation is:

$$M=334.74h^{1.050} \quad (R^2=0.954) \tag{2}$$

Exponents in both expressions are close to 1, and their coefficients also approximate each other. Hence, as in Chacaizhugou subwatershed, it can also be concluded that the vegetation and terrace practices in Qiaozidonggou subwatershed have not changed its runoff-sediment yield relationship and their contribution to soil conservation is therefore only made by reducing runoff volume.

### 2.5 Large-size watershed scale

In small watersheds, the flow convergence and sediment transport are dominated by the hillslope process. However, with the drainage area increasing, the channel processes play a more and more important role[23]. The observation in Ohio revealed that the sediment yield from small basins correlated well with rainfall characteristics and vegetative covering factors, whereas yield from a large basin correlated well with river flows. Similar trends can also be found for catchments in Minnesota ranging in size from 362 km$^2$ to 38600 km$^2$ [38]. Generally, the larger the watershed is, the less influence the hillslope processes exert on sediment processes. Vegetation or other slope measures for soil conservation may exert significant effects on the hillslope processes; however, the runoff-sediment yield relationship for large-size watershed is largely determined by channel processes rather than by hillslope processes. Hence, it seems extremely difficult for vegetation or other slope measures to change the runoff-sediment yield relationship when a large-size watershed is considered.

Weihe River (Fig. 1b) is the largest tributary of the Yellow River. About an area of 47 461 km$^2$ in it, that is, around 75% of the total basin area, suffered from soil loss. Up to the end of 1996, the cumulative areas of terrace construction was 5825 km$^2$, forest plantation 7566 km$^2$ and grass growing 2054 km$^2$. All of these areas occupy 31.4% of the area suffered from soil loss in total. In addition, numerous dams were constructed and they made greater contribution to sediment reduction than to slope measures. After being excluded out of the contribution of these dams, the contribution of the slope measures can be figured out for four periods: during 1954–1969, runoff is decreased by 13.09 million m$^3$ and sediment decreased by 2.07 million t; during 1970–1979, runoff decreased by 49.41 million m$^3$ and sediment decreased by 8.13 million t; during 1980–1989, runoff decreased by 131.11 million m$^3$ and sediment decreased by 17.44 million t; during 1990–1996, runoff decreased by 139.43 million m$^3$ and sediment decreased by 24.43 million[39]. Decreasing runoff volume by one unit by these slope measures will result in a sediment reduction of 632 kg/m$^3$, 608 kg/m$^3$, 752 kg/m$^3$ and 571 kg/m$^3$ for these four periods, respectively. No significant difference is observed among them despite an expected difference in management intensities and extents for the four periods. This suggests that for these four periods, the same runoff-reduction will result in approximately the same sediment-reduction, and vegetation and other slope measures have little effect on sediment yield per unit runoff in Weihe River.

Some studies have also reported a decreased sediment concentration and a sediment-reduction rate higher than the runoff-reduction rate after the conservation management starts in many watersheds on Loess Plateau[40]. This observation can be attributed to the engineering items within channels such as check dams. These dams, which are widespread in Loess Plateau, can reduce the slope of channels and thereby decrease the sediment transport capacity of the flow[31].

In 1993, Cao[41] plotted the sediment discharge rate against the water discharge based on the data observed at Atengxire (upper drainage area is 330 km$^2$), Wangdaohengta (3839 km$^2$), Wenjiachuan (8645 km$^2$) stations in the Kuyehe river basin (Fig. 1a). It was found that the points for different periods, and therefore for different management intensities, intermixed with each other. Conservation measures taken in the Kuyehe river basin mainly included terraces, vegetated slopes and check dams. However, the contribution of the check dam to sediment reduction was negligible relative to other measures. In 1970s, the check dam contributed around 0.32% of the total trapped sediment and in 1980s, the dam contributed around 0.40%[42]. For this reason, the flow-sediment relationship is invariable with time.

## 3 Conclusion and discussion

(1) At the plot scale, vegetation does not only reduce runoff volume, but also change the runoff-sediment yield relationship. Both ways significantly contribute to the effect of the vegetation on the erosion process. Hence, the sediment-reduction rate is expected to be higher than the runoff-reduction rate at this scale. However, vegetation measures are insufficient to control mass movement and can also hardly change the transport capacity of water flows in channels. Thus, at the watershed scales, where gully erosion and mass wasting processes are dominant, vegetation cannot change the runoff-sediment yield relationship. Moreover, the larger the watershed, the less influence the hillslope processes exerted on sediment proc-

esses. Hence, at the watershed scale, vegetation helps reduce the sediment yield simply by reducing runoff volume, leading to a sediment-reduction rate close to runoff-reduction rate. Vegetation or other slope measures for erosion control, which are of the greatest runoff-reduction rate, are therefore expected to have the greatest benefit to soil conservation at the watershed scale in hilly loess areas.

(2) An analysis about two individual events in Yangdaogou and Chacaizhugou subwatersheds shows that the event mean sediment concentration in the managed watershed is even likely to be higher than that in the non-managed watershed because of the effect of the low-magnitude events prior to the selected events. Theoretically, owing to the vegetation effect on the rainfall-runoff process, small flood events are more likely to occur in the forested watershed under the same rainfall events. As a result, coarse sediment is more likely to be stored in gully channels prior to high-magnitude flood events and then the mean sediment concentrations for these large events in managed watersheds are likely to be higher than that in non-managed watersheds. However, this phenomenon is not commonly observed in Yangdaogou and Chacaizhugou subwatersheds. One possible reason for this is that the silty soil in the study area does not allow a rapid accumulation of coarse sediment in gullies. However, in sandy loess belt on Loess Plateau, where the sand content is relatively high, a large amount of coarse sediment may often accumulate in gullies prior to large flood events. As a result, in the sandy loess belt on Loess Plateau, it may be commonly observed that the event mean sediment concentrations for large events increase after vegetation is established.

(3) In one region, where sediment supply is sufficient and thus sediment yield only depends on the capacity of the sediment transport system, if sediment flux still remains transport-limited after vegetation is established, then the runoff-sediment yield relationship is also expected to remain unchanged after vegetation is established since vegetation can hardly change the channel topography and thus change the capacity of the sediment transport system.

(4) In some sense, the conservation management practices can be translated to land use or land cover change in the study area. Land use or land cover change generally occurs at the slope land and has little effect on the channel topography. If the land use or land cover change cannot control mass-wasting processes effectively so that the sediment supply also remains abundant, then such a change cannot result in a significant change in the runoff-sediment yield relationship in the hilly loess area, and its effect on sediment yield at the watershed outlet is also achieved simply by changing the rainfall-runoff relationship.

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