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ORIGINAL ARTICLE

Scale effect on sediment yield from sloping surfaces to basins in hilly loess region on the Loess Plateau in China

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Abstract Based on data from two runoff plots and ten stations in hilly loess region Dalihe drainage basin ranging in area from 0.0006 to 3983 km^2 on the Loess Plateau, the relationship between mean annual specific sediment yield (Y_s) and drainage area (A) is studied, which is different from those for many other drainage areas of the world, neither at the scale of whole basin nor at local scale on the Loess Plateau. With increasing drainage area, the mean annual specific sediment yield experiences two peak values: the first peak value appears at 0.00408 km^2 in area corresponding to the whole slope surface, and the second peak value appears at 96.1 km^2 in area. The non-linear variation in the Y_s–A can be explained as follows: the first peak value can be explained by the abrupt increase in slope gradient and flow shear stress resulting in highly increased sediment concentration and specific sediment yield. And the second peak value can be explained by the combined influence of flow shear stress and drainage density, represented by dimensionless variable Ω.

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Introduction

Soil erosion as an environmental problem varies enormously in space both in terms of the total magnitude of erosion and in the type of erosion occurring (Kirkby and Morgan 1980). As an important theoretical issue in earth sciences studies on spatial scale effect on soil erosion have been published in hydrology and geomorphology (Church and Slaymaker 1989; Owens and Slaymaker 1992; Andrle 1996; Imeson and Lavee 1998; Yin and Wang 1999; Xu and Yan 2005; Yan and Xu 2006). Drainage area (A), related with almost all process variables, is generally correlated with specific sediment yield (Y_s), and numerous studies reported a negative correlation exists between specific sediment yield and basin area (Fig. 1a). According to Chorley et al. (1984) and many others, the higher relief ratio and less broad floodplains providing the sediment less opportunity to deposit in small basins than in relatively bigger basins explain this phenomenon. In contrast, data from British Columbian rivers reveal a pattern of increasing specific sediment yield at all spatial scales up to 3×10^4 km^2, which results from, explained by Church and Slaymaker (1989), the dominance of secondary remobilization of Quaternary sediments along river valleys over primary denudation of the land surface (Fig. 1b). On the Loess Plateau, Xu and Yan (2005) found the specific sediment yield increases with drainage area to some maximum values where the drainage area is 2,000–3,000 km^2, followed by a

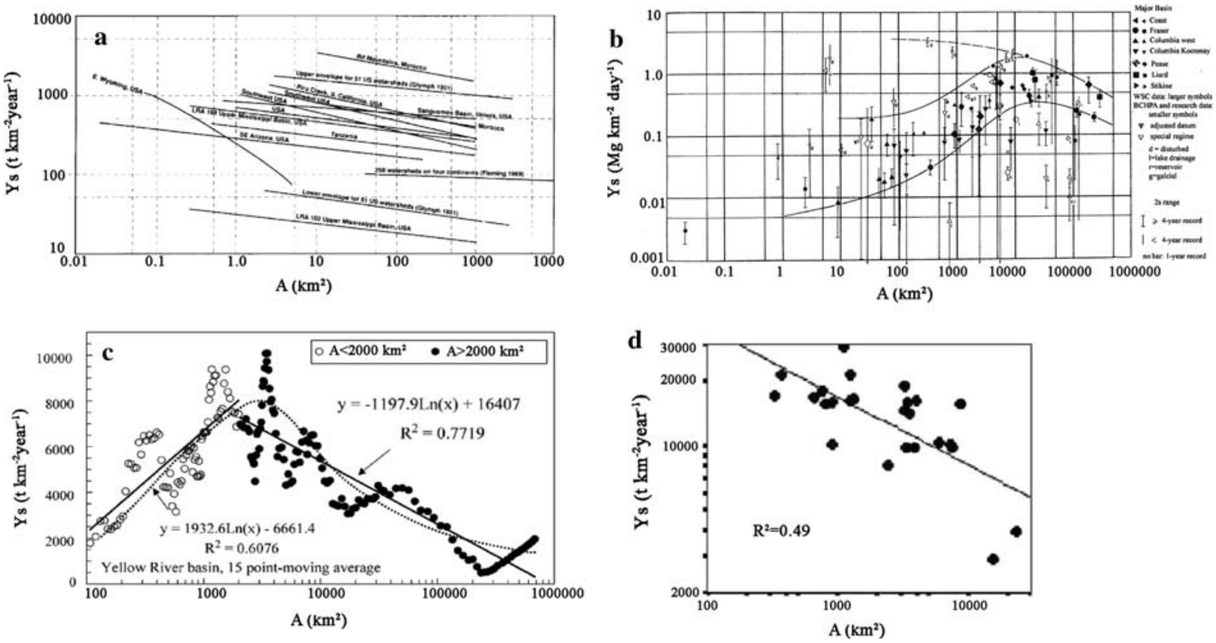


Fig. 1 Relationships between specific sediment yield (Y_s) and basin area (A) based on data from **a** USA and some other countries (modified from Owens and Slaymaker 1992), **b** British Columbian rivers (modified from Church and Slamaker 1989), **c** Yellow River on the Loess Plateau, China (modified from Xu and Yan 2005), and **d** hilly loess region on the Loess Plateau, China (modified from Yan and Xu 2006)

decrease when the drainage area increases further (Fig. 1c). The loess thickness along the longitudinal profiles of the Yellow River and its tributaries and the stream power explained this phenomenon by Xu and Yan (2005). Yan and Xu (2006) further studied the scale effect of drainage area of each subzone of Loess Plateau on specific sediment yield and discovered when the drainage area is over 100 km^2 it presents a monotonic negative trend with drainage area in hilly loess region (Fig. 1d), in addition to the loess thickness along the longitudinal profiles of the rivers, Yan and Xu (2006) explained it further by geometric characteristics of the channels over the cross-sections controlled by hydrometric station.

As the most severe soil and water loss area in the world, over 60% of the land area on the Loess Plateau has been subjected to soil and water loss (Shi and Shao 2000). The Chinese government has paid increasing attention to control of soil erosion on the Loess Plateau, and the small basin scale is regarded as the basic unit to integrate soil erosion control (Fu 2006). Therefore, to study the specific sediment yield in small drainage areas of different spatial scales and to disclose the mechanism of soil erosion are beneficial to prevent and control soil loss.

Though Xu and Yan (2005) and Yan and Xu (2006) have studied the scale effect of drainage area on specific sediment yield on Loess Plateau, all the drainage areas studied are in excess of 100 km^2 (Fig. 1c, d), and the broader drainage area must meet more environmental variables related with specific sediment yield than little ones (Jetten et al. 1999). The objectives of this study are to examine the relationship between different spatial scales from sloping surface to drainage basins ranging from 0.0006 to 3,893 km^2 in areas and mean annual specific sediment yields, and to explain it in terms of geomorphic and other factors.

Description of study area and data sources

The outline of the study area

Dalihe River is a secondary tributary of Yellow River belonging to Wudinghe River, the drainage basin of which covers an area of 3,893 km^2 (from 108°54′ to 110°15′E and 37°14′ to 37°49′N, 900 to 1700 mm a.s.l.) (Fig. 2), the areas and class ratings of the two runoff plots and ten drainage basins with different spatial scales studied within which are listed in Table 1. Dalihe drainage basin possesses Malan loess with less than 40% clay particles leading to its large porosity and easy erodibility (Kimura et al. 2005).

The mean annual precipitation is 500 mm, predominantly falling from June to September. The rainstorms characterized by short duration and hard rainfall

Fig. 2 Map showing the location of Dalihe drainage basin

intensity ranging from 0.8 to 3.5 mm s^{-1} as well as the formed Hortonian flow make the loess soil surface to be steep-gullied small basins. The grass coverage is about 10%, and the forest coverage 10–15% with little change in this region (Wang 1991). Human activities represented by human density 150 inhabitants per square kilometer are almost the same, and the agricultural intensity is almost equal represented by reclamation ratio 50–60% (Cai 1994).

Data source

The data runoff depth, suspended sediment concentration and sediment yield in the study area come from hydrometric stations that are established and managed by the Yellow River Conservancy Commission (1961–1969). The procedures used for hydrological survey and sampling at hydrometric stations in China are basically the same as used internationally. For most stations, the hydrological variables are available since 1960. Since human activity, especially the construction of hydrologic engineering works, has increased markedly since 1970. Data were chosen for the period 1961–1969 for analysis to study the natural condition without human intervention with respect to scale effect on specific sediment yield. The data used include drainage area (A), mean annual suspended sediment load (Q_s), and mean annual runoff depth (H) from the runoff plots and drainage basins. The specific sediment yield (Y_s) is calculated as $Y_s = Q_s/A$.

To explain the non-linear variation of specific sediment yield with drainage area, the data of drainage density and slope gradient will be involved. Drainage density and slope gradient were obtained from 1:100000 digital elevation model (DEM). The individual basin length in the river flow direction was obtained through measure tool of ArcGIS, and the difference in elevation was measured from the contour line extracted from DEM, and then average slope gradient was calculated as the height of the basin divided by its length. The drainage density was obtained through dividing basin area by the total river length measured by the product of the amount of pixels of each gully/channel and its tributaries past through and the pixel resolution.

Result

Based on data from two runoff plots and ten hydrometric stations in Dalihe drainage basin and its tributaries, the relationship between mean annual specific sediment yield and runoff plot/basin area is plotted in

Table 1 Introduction of the characteristic of the study sites within Dalihe drainage basin (Data from Yellow River Water Conservancy Commission (1961–1969))

Runoff plot or river section	Drainage area (km^2)	Drainage type	Gully density (km/km^2)	Slope gradient (‰)
No. 2	0.0006	A slope Mao in Tuanshangou	×	444
No. 7	0.00408	A whole slope surface in Tuanshangou	×	840
Tuanshangou	0.18	A tributary of Shejiagou	0.63	135
Shejiagou	4.26	A tributary of Chabagou	0.82	11.5
Tuoerxiang	5.74	A tributary of Chabagou	0.85	2.7
Sanchuankou	21	A tributary of Chabagou	0.78	2.23
Xizhuang	49	Chabagou	1.01	15
Dujiagou	96.1	Chabagou	1.06	8.36
Caoping	187	A tributary of Dalihe	1.05	7.57
Qiangyangcha	658	Dalihe	1.01	8.26
Lijiahe	802	A tributary of Dalihe	0.82	7.72
Suide	3893	Dalihe	0.88	6.83

No. 2 and No. 7 indicate the No. 2 and No. 7 runoff plots in Tuanshanou basin. × represents no gully development. Whole slope surface includes three parts inter-gully land, slope Mao, and gully slope, for a detailed introduction of them, please also see Chen (1999)

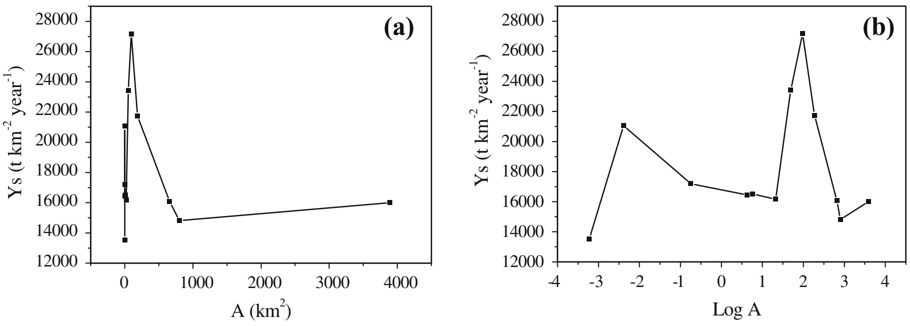


Fig. 3 Relationship between mean annual specific sediment yields (Y_s) and drainage area (A) based on data from two runoff plots and ten gauging station in hilly loess region (**a**) plot of Y_s against A, and (**b**) plot of Y_s against logarithmic transformed drainage area (Log A)

Fig. 3a. For large difference in areas of runoff plots and other drainage basins (Table 1), the curve change is not clear when the area is less than 96.1 km^2, then the mean annual specific sediment yield vs. log-transformed drainage basin area is re-plotted in Fig. 3b, which shows a non-linear Y_s–A relationship with double peak values. One peak value of mean annual specific sediment yield 21,000 t km^{-2} year^{-1} appears at an area of about 0.00408 km^2, corresponding to at the scale of whole slope surface, followed a decrease when the drainage area increases further, however, when the drainage area reaches 96.1 km^2, the mean annual specific sediment yield again reaches the other peak value 27,000 t km^{-2} year^{-1}, and again it decreases when the drainage area increases further.

Discussion

Relationship between runoff depth and Y_s with drainage area

In the studied slope surfaces/drainage basins of different spatial scales, vegetation type, land use, and soil type and texture are almost the same, and regarded as constants in this paper. According to Hovius (1998), runoff determines to a certain extent the transport capacity of the fluvial system and also refers to the amount of water available for hillslope erosion. In Dalihe drainage basins on the Loess Plateau, sediment supply is generally abundant and non-limiting (Yan and Xu 2006; Xu and Cheng 2002), and runoff depth is regard as one of the best variables to model specific sediment yield (Wang et al. 1982; Chen and Wang 1999; Nearing et al. 2005). Therefore, together with mean annual specific sediment yield mean annual runoff depth is plotted against drainage area in Fig. 4 to explain the change of specific sediment yield, which shows that when the drainage area is over 5.74 km^2, mean annual specific sediment yield has the same changing trend as that of the mean annual runoff depth with drainage area; however, the mean annual specific sediment yield presents inverse relationship with runoff depth when the drainage area is less than 5.74 km^2. This means mean annual specific sediment yield must be dominantly influenced by other factors in addition to mean annual runoff depth when the drainage area is less than 5.74 km^2, which will be explained in the followed sections of this paper.

Scale effect related with transporting capacity of water flow

According to Xu (1999), for either slope or channel flows, flow shear stress can be expressed as follows:

$$T = R_m HJ = \rho gHJ \quad (1)$$

where T is flow shear stress in N m^{-2}, R_m is bulk density of muddy water in N, ρ is bulk density of muddy water in kg m^{-3}, g is gravitational acceleration in 9.8 N kg^{-1}, H is runoff depth in mm, and J is drainage gradient in ‰ at the basin outlet. In loess hilly regions on the Loess Plateau, sediment supply is generally abundant and non-limiting (Yan and Xu 2006; Xu and

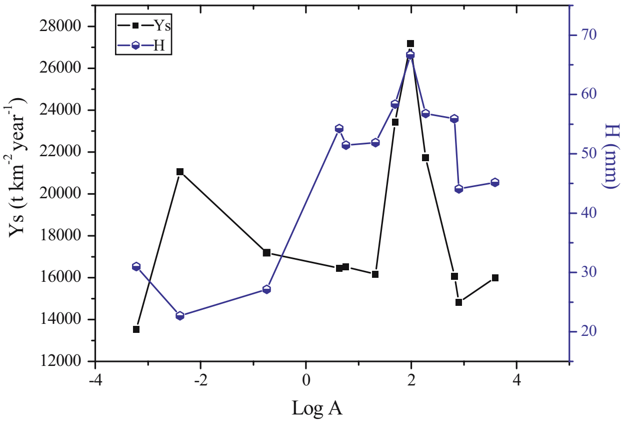


Fig. 4 Runoff depth (H) changes together with specific sediment yield with logarithmic transformed drainage area (Log A)

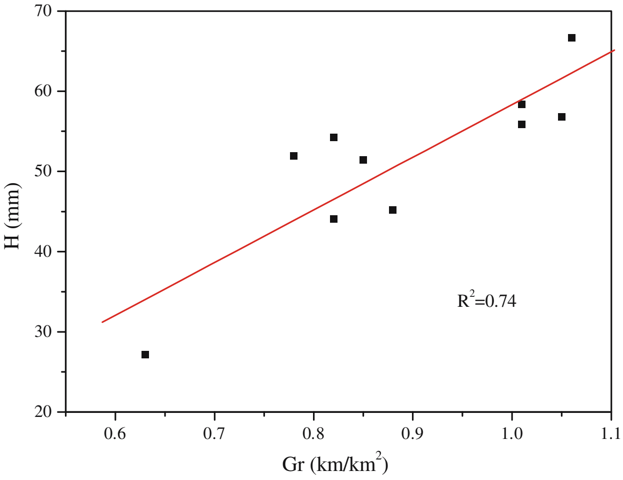


Fig. 5 Relationship between drainage density (*Gr*) and runoff depth (*H*) for the drainage areas over 0.00408 km^2

Cheng 2002), under this condition, larger flow shear stress often leads to higher sediment concentration (Chen and Wang 1999).

Equation 1 shows the importance of runoff depth in determining the value of flow shear stress. Mean annual runoff depth and mean annual specific sediment yield, according to Lane et al. (1997), are associated highly with drainage density, which is a most important spatial measure of the channel system in a drainage basin indicating the confluence capacity of water flow in a drainage basin. Figure 5 verifies the positive relationship between the runoff depths in different drainage areas in hilly loess regions and gullied density (R^2 = 0.74), which means drainage density must not be neglected when we study the Y_s–A relationship.

Explanation for the Y_s–A relationship

Figure 3 indicates that at the area of about 0.00408 km^2 the specific sediment yield reaches its first peak value 21,000 t km^{-2} year^{-1} that corresponds to No. 7 whole slope surface area. In slope Mao region (here indicating No. 2 runoff plot), the erosional material is not easily transported for its gentler slope gradient and lower flow shear stress, and the erosion is mainly dominated by sheet erosion (Chen and Wang 1999). In the lower part of the whole slope surface, abrupt increase in slope gradient and flow shear stress lead to the development of drainage lines in the form of rills or even ephemeral gullies, and significant changes in specific sediment yield occur from non-rilled to rilled slopes (Desmet et al. 1999; Woodward 1999; Zheng et al. 2005; Valentin et al. 2005).

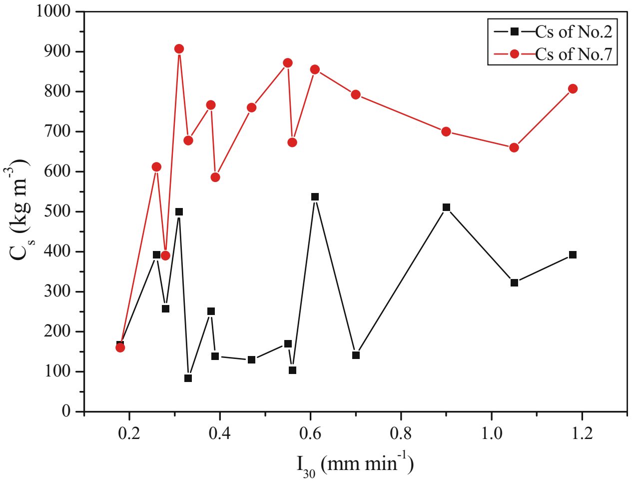
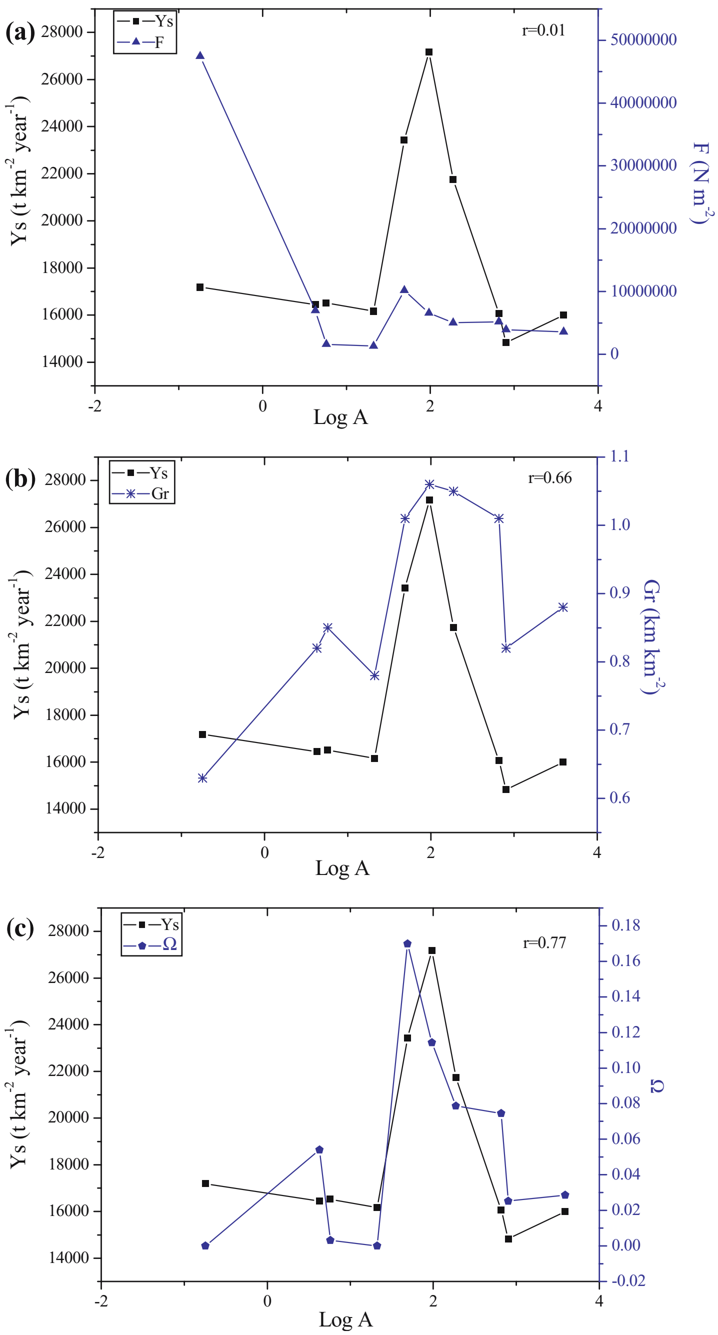


Fig. 6 Relationship of the sediment concentration (C_s) between the slope Mao No. 2 and the whole slope surface No. 7 with the increase of maximum 30-min rain intensity (I_{30})

Sediment yield per runoff depth is regarded as the transporting capacity of flow, which equals sediment concentration in values though having different physical senses (Lane et al. 1997; Fei and Shao 2004). Storm event-based suspended sediment concentrations of No. 2 and 7 runoff plots in Tuanshangou are plotted against maximum rainfall intensity in 30 min in Fig. 6, which indicates the sediment concentration on slope No. 7 runoff plot is higher than that on slope Mao No. 2 runoff plot. A vast number of studies demonstrated that the increased slope steepness can greatly enhance sediment concentration and then the specific sediment yield (Lane et al. 1997; Fox and Bryan 1999; Chen et al. 2006). Study on Wangjiagou drainage basin by Chen and Wang (1999) showed when water flow passes the steep gullied slope, the net increase in sediment load occupies 54.46% of the total of the whole slope surface. Furthermore, at the interface of slope and gullied area, for steeper slope gradient other erosional forms, including landslide and floods, often occur. Triggering events, such as critically intense rainfall and earthquakes, often lead to natural landslide erosion (Hovius et al. 1997). In addition, many human activities, notably intensive agriculture, mining, construction, and road building, promote landslides by undercutting hillslope or by altering hillslope hydrology (Syvitski 2003; Syvitsky et al. 1987). The gravitational erosion mentioned above might occur in the loess hilly slope. Though the mean annual runoff depth is very little (Fig. 4), the higher sediment concentration resulting from the abrupt increase in slope gradient and developed rill/ephemeral gully/gully or even gravitational action on the whole slope surface forms the first peak value in mean annual specific sediment yield.

The second peak value in annual specific sediment yield can be explained by the combined action of flow shear stress and drainage density. The plotted curve of flow shear stress against drainage area shows almost similar trend with mean annual specific sediment yields (Fig. 7a), a fact indicating some possible cause-effect relationship between these two curves. Though correlation coefficient (0.01) between them is low, for large decrease in flow shear stress from whole slope surface to larger spatial scale not leading to so much decrease in specific sediment yield. If Tuangshangou drainage basin were deleted from Fig. 7a, the correlation coefficient of them is up to 0.66, which means spatial scale is still intensively influenced by flow shear stress. Larger drainage density can fragment the land surface, reduce water loss, enhance the capacity of confluence of water flow in a drainage basin, and then highly correlated with mean annual runoff depth and specific sediment yield (Zhao et al. 2003; Lane et al. 1997; Fu et al. 2006), which is a most important spatial measure of the channel system in a drainage basin. Figure 7b shows the correlation coefficient between drainage

Fig. 7 Relationship between mean annual specific sediment yield (Y_s) for the logarithmic transformed drainage areas (Log A) over 0.00408 km^2 and **a** flow shear stress (F), **b** drainage density (Gr), and **c** dimensionless variable Ω



density and mean annual specific sediment yield reaches 0.66 indicating the importance of drainage density in influencing mean annual specific sediment yield. Therefore, the second peak value can be explained by the combined action of flow shear stress and drainage density. In order to show the combined influence on specific sediment yield, for different orders of magnitude between flow shear stress and drainage density, standardized values of flow shear stress and drainage density are obtained by following formula:

$$\Omega = (X_i - X_{\min})/(X_{\max} - X_{\min}) \tag{2}$$

Where Ω is the standardized value, X_{i}, $X_{\max}$ and $X_{\min}$ are the original, maximum and minimum values of each dataset of flow shear stress and drainage density, respectively. Dimensionless product (Ω) by standardized values of flow shear stress and drainage density is plotted against mean annual specific sediment yield in Fig. 7c. Compared with the correlation coefficients between flow shear stress, drainage density and mean annual specific sediment yield, the correlation coefficient (0.77) of Ω and specific sediment yield is highly improved. On the left limb of the Ω curve with drainage area, the highly decreasing Ω value trend only leads to a little decrease in mean annual specific sediment yield, with the continued decrease in Ω value, the mean annual specific sediment yield reaches its minimum value at the area of 21 km^2. Unlike bigger drainage basins, where drainage slope decreases with the increasing drainage area (Xu and Yan 2005), smaller drainage area often has much variation of slope gradient that greatly influences the flow shear stress (Fig. 7a). With drainage area increased further, the increased flow shearing stress and gully density produce the highest Ω value that makes the other peak value 27,000 t km^{-2} year^{-1} appeared at about 96.1 km^2. When the drainage area increases furtherer than 96.1 km^2, the dimensionless Ω value represented the synthesized action of flow shear stress and drainage density follows a decreasing trend, that makes the mean annual specific sediment yield decreases, which is in agreement with the changed pattern of mean annual specific sediment yield when the drainage area in over 100 km^2 in hilly loess region on the Loess Plateau studied by Yan and Xu (2006).

Cautionary note

Specific data, for example the data of threshold drainage area values or mean annual specific sediment yield in Fig. 3 must be interpreted with caution and seen as qualitative rather than quantitative expressions. Short record lengths, not too many runoff plots/hydrometric stations, and measure errors in the face of very high temporal and spatial variability of hydrologic processes make the threshold values and corresponding drainage areas subject to revision as more data and understanding are gained.

While it is likely that more data and understanding may switch the threshold values of mean annual specific sediment yields and even the corresponding drainage areas to some extent, the flow shear stress and drainage density remain important in determining the specific sediment yield, and the threshold values in Fig. 4 will remain existed.

Conclusions

The present study is conducted from sloping surface to drainage basins ranging from 0.0006 to 3890 km^2 in area in hilly loess region on the Loess Plateau, where the soil type and texture, vegetation coverage, land use type, and human activities are almost the same and be regarded as constants in influencing specific sediment yield in this paper. Result indicates that mean annual specific sediment yield presents non-linear Y_s–A relationship in hilly loess region on the Loess Plateau, which does not follow monotonic negative one, nor does a unimodal distribution pattern, but a bimodal distribution. The first peak value appears at the scale of whole slope surface that is 0.00408 km^2 in area, which can be explained by the abrupt increase in slope gradient, that leads to occurrence of rill or even ephemeral gullied erosion resulting in highly increased sediment concentration, though for lower runoff depth at this area, the peak value still appears at this scale. When the drainage area increases further, the lower sediment concentration for lower flow shear stress and not higher drainage density make the specific sediment yield experience a decreasing trend. With the increase in drainage area again, the combined action of flow shear stress and drainage density reaches its greatest status, and the second peak value in mean annual specific sediment yield appears at the drainage area 96.1 km^2, and then followed a decrease in specific sediment yield with the further increase in drainage area.

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