Sediment Delivery across Multiple Spatio-temporal Scales in an Agriculture Watershed of the Chinese Loess Plateau

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Abstract: There is a consensus that sediment delivery ratio in the Chinese Loess Plateau is close to 1 at the inter-annual timescale. However, little information is available about the sediment delivery at finer timescales. We evaluated the sediment delivery from plots to watersheds at the event or intra-annual, annual, and inter-annual timescales within the Wudinghe river basin, a 30,261 km² basin in the Loess Plateau. We calculated the ratio of sediment output to sediment input and presented the temporal change of the channel morphology to determine whether sediment deposition occurs. Although a single flood event frequently has a sediment yield exceeding 10,000 t km⁻², sediment deposition rarely occurs except during some small runoff events (sediment yield < 5000 t km⁻²) or dry years (sediment yield < 10,000 t km⁻²) when moving from slopes up to the main channels of the Wudinghe River. This observation suggests a sediment delivery ratio close to 1 even at the event or intra-annual and the annual timescales, but not necessarily at the inter-annual timescale. Such a high sediment delivery ratio can be related to hyper-concentrated flows, which have very strong sediment transport capacity even at

low flow strength. Because hyper-concentrated flows are well-developed in the whole Loess Plateau, a sediment delivery ratio close to 1 below the inter-annual timescale possibly remains true for other rivers in the Loess Plateau.

Keywords: Sediment delivery ratio; Spatial scale; Soil erosion; Sediment yield; Loess Plateau

Introduction

Soil erosion and sediment delivery are important environmental problems and have long been recognized as major concerns for sustainable development (Alatorre et al. 2010; Sadeghi et al. 2013). Generally, only a small fraction of eroded sediments will arrive at the basin outlet and be represented in the basin sediment yield (Walling 1983; Alatorre et al. 2010). A dimensionless variable, termed sediment delivery ratio (SDR), was often used to link on-site erosion with downstream sediment yield (Walling 1983; Lane et al. 1997; Lu et al. 2005; De Vent et al. 2007). SDR is most commonly defined as the ratio of

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sediment yield to gross erosion. Despite some criticism including practical difficulty in estimating gross erosion (e.g. Lane et al. 1997) and the conceptual validity (Parsons et al. 2006), SDR remains a practical approach for sediment load predictions at the watershed scale (Notebaert et al. 2009; Vigiak et al. 2011; Shi et al. 2013; Shi et al. 2014).

SDR closely depends on the spatial and temporal scales over which sediment yield and gross erosion are measured (Lu et al. 2005). It has been well known that SDR typically decreases with increasing basin size due to the gentle slope and the channel gradient and increasing opportunities for deposition associated with large basins (Walling 1983; Lu et al. 2005). Over millennial timescales, SDR should approach unity (Lu et al. 2005; De Vente et al. 2007). In contrast, values of SDR reported in contemporary literatures, most of which do not rely on actual empirical data but spatially distributed models to obtain gross erosion rates, range from less than 0.1 to almost 1 (Walling 1983). Research efforts are therefore needed to investigate SDR at various spatio-temporal scales.

The Chinese Loess Plateau, located in the middle Yellow River basin, suffers from a soil loss rate higher than $10,000 \text{ t km}^{-2} \text{ a}^{-1}$ (Gong and Xiong 1980). Gong and Xiong (1979 and 1980) compared areal sediment yield of variable-sized basins in the Loess Plateau, finding that stream channels of various orders are essentially in equilibrium between aggradation and degradation; thus, they suggested a SDR very close to 1 at the inter-annual timescale. Hyper-concentrated flows are well developed in the Loess Plateau (Xu 1999). The subsequent calculations by Mou and Meng (1982) demonstrated that almost all sediment loads (>95%) are wash loads as a result of the combination of the strong capacity of hyper-concentrated flows to suspend coarse sediments (Pierson 2005) and the fine texture of the loess ($d_{50} < 0.05 \text{ mm}$); this mechanism physically enables a SDR close to 1. Since then, a SDR close to 1 across a wide range of basin sizes in the Loess Plateau at the inter-annual timescale has acquired broad acceptance (e.g., Cai 1998; Jing et al. 1993; Lu et al. 2005; Walling 1983 and 1999; Xu 1999; Xu and Sun 2004). Nevertheless, little information is available on sediment delivery below the inter-annual timescale. As with other regions around the

world (Molier et al. 2004; Shi et al. 2004; Marques et al. 2008; Angulo-Martínez and Beguería 2009), a small number of extremely intense rainfall events are typically responsible for the largest proportion of soil erosion and sediment delivery in the Loess Plateau. A single flood event, which frequently causes a soil loss exceeding $10,000 \text{ t km}^{-2}$, can contribute up to 90% of the annual sediment yield (Gong 1988; Liu et al. 2013). Hence, there is a need to address the sediment delivery at the event timescale or other timescales finer than several years.

The object of this study is to evaluate the sediment delivery across a range of spatio-temporal scales in the Loess Plateau, with a special attention to the timescale allowing a SDR close to 1. Using observations at a series of nested sites, we evaluated the sediment delivery from plots to watersheds within the Wudinghe River basin (Figure 1), a tributary of the middle Yellow River, at the event or intra-annual, annual, and inter-annual timescales.

1 Study Area and Data Source

The Wudinghe River drains an area of $30,261 \text{ km}^2$. The river runs across eolian sandy areas in its upper part and across loess areas in its lower part (Figure 1(a)). Typical of the hilly loess areas, the loess mantle in the lower part is generally thicker than 100 m. Loess is loosely compacted and susceptible to water erosion. The climate is semi-arid and temperate. Vegetation cover is sparse. Mean average annual precipitation is about 450 mm in the loess areas and decreases to 400 mm in the eolian sandy areas. The terrain in loess areas is very precipitous and deeply dissected. Stream channels deeply incise into bedrock. Mass wasting such as slumping, sliding and collapsing is active on valley side slopes. More details of the Wudinghe basin can be found in Xu (2011) and Li et al. (2007).

The Wudinghe basin has a long history (> 1000 years) of agriculture cultivation. Before 1970, the basin was intensively cultivated except steep areas. For instance, the percent area of the cultivated land was as high as 65%, whereas the percent area of the land steeper than 20° was as high as 68% in the 205 km^2 Chabagou Creek, a second-order tributary of the Wudinghe River

Figure 1 Locations of the study area and gauging stations: (a) the Wudinghe River, (b) the Chabagou Creek (modified from Zheng et al. (2011)), and (c) the Tuanshangou Creek (modified from Zheng et al. (2011)). The numbers for the gauging stations correspond to the station numbers in Table 1. The Plot numbers in (c) correspond to those given in Table 2 in Zheng et al. (2012). Plot length was presented in (c). Letters in (b) correspond to the reach codes in Table 3.

(Figure 1(b)). Watershed management for soil conservation was not extensively implemented. In contrast, the basin was under intensive soil conservation after 1970; especially, a large number of hydrologic engineering works such as check dams intercepted large quantities of sediment. Hence, the post-1970 period was not considered in the present study. In addition, many experimental sites were not operated before 1959. As a result, we limited our analysis to the period 1959–1969. During this period, the observed sediment yield in the loess areas of the Wudinghe basin was as high as $19,000 \text{ t km}^{-2} \text{ a}^{-1}$.

Unless stated otherwise, all data used in this study were obtained from the Yellow River Water Conservancy Commission (YRWCC). The YRWCC stream-gauging crews conducted all measurements following national standard procedures issued by

the Ministry of Water Resources of the PRC (1962). The procedures are essentially identical to the international procedures (Xu and Yan 2005). See Zheng et al. (2012) and Zheng et al. (2013) for details of the measurement procedures.

The sediment yield data we used involve three timescales: sediment yield per unit area for a single event (SSY_e , t km^{-2}), sediment yield per unit area for a single year (SSY_a , t km^{-2}), and the mean annual sediment yield per unit area (SSY , $\text{t km}^{-2} \text{ a}^{-1}$). SSY is the arithmetic mean of SSY_a . Sediment delivery pathways include both stream channels and upland slopes. Deposition whether on slopes or along stream channels would lead to a SDR smaller than 1. Hence, the evaluation of SDR should consider processes both on slopes and along stream channels. Observations at 13 gauging stations (Table 1) and 5 runoff experimental plots

Table 1 Gauging stations or experimental watersheds in the Wudinghe basin

River	Stations or watershed ^a	Area (km ²)	SSY ^b (t km ⁻² a ⁻¹)
Tuanshangou	Tuanshangou (#3)	0.18	19,751
Shejiagou	Shejiagou (#4)	4.26	16,937
Tuoerxianggou	Tuoerxianggou (#5)	5.74	14,628
Liujiagou	Sanchuankou (#6)	21	16,948
Chabagou	Xizhuang (#7)	49	21,977
Chabagou	Caoping (#9)	187	21,763
Dalihe	Qingyangcha (#10)	662	16,001
Xiaolihe	Lijiahe (#11)	807	15,784
Dalihe	Suide (#12)	3893	16,680
Yuxihe	Yulin(#16)	4938	846
Wudinghe	Zhaoshiyao(#19)	15,325	2152
Wudinghe	Dingjiagou(#20)	23,422	3711
Wudinghe	Chuankou(#21)	30,217	6945
Wudinghe	IR#3	9355	19,341

Notes: ^a The numbers in parentheses correspond to the station numbers given in Figure 1. IR#3 denotes the reach between station #21 and the confluence of the Yuxihe River into the Wudinghe River (See Figure 1(a)).

^b SSY involves the period 1959-1969.

were used. The watersheds upstream of the gauging stations have areas ranging between 0.18 and 30,217 km². The number of the SSY_a data for a gauging station varied from 8 to 11, with a mean of 10.3 over the period 1959-1969. The experimental plots we used are all located in the Tuanshangou sub-watershed (Figure 1(c)), a headwater basin in the Chabagou watershed. The plots were all used as farmland and had a length varying from 20 to 164 m (Figure 1(c)). The number of recorded events ranged from 36 to 58 over the monitoring period 1961-1969. Detailed information is available in Table 2 of Zheng et al. (2012). Whether land use or topography of these plots were typical of the loss area of the Wudinghe basin.

It should be noted that the observed sediment load includes both suspended and bed loads on slopes but only the suspended load for watersheds. In the subsequent text, the term sediment yield refers to the total load for plots and the suspended load for watersheds. As mentioned above, however, the calculation by Mou and Meng (1982) demonstrated that almost all sediment loads

(>95%) are wash loads in the Loess Plateau. For this reason, the measured sediment load can be regarded as the total load from plots to watersheds.

2 Methods

Following Wischmeier and Smith (1978), this study defined the gross erosion to include all eroded sediments both on slopes and within or along stream channels. It should be noted that mass-wasting materials should not be included into the gross erosion unless they are dislodged into flows. Such a definition implies that SDR can never exceed 1 and a SDR of 1 is simply identical to no deposition loss. We used the ratio of sediment output to sediment input to determine whether deposition loss occurs. Gross erosion is the summation of erosion from all sources within the watershed, whereas sediment input into a river reach includes both what is delivered from its upper reach plus the contributions from the tributaries. Deposition occurs if the ratio is smaller than 1, whereas sediment entrainment occurs if the ratio is larger than

1. For a river basin, SDR is not equal to 1 unless the ratio is consistently larger than or equal to 1 from upland slopes up to the main stream.

Corresponding to the three timescales we examined, we calculated the ratio of sediment output to sediment input for a single event (R_e), for a single year (R_a), and for the whole period 1959-1969 (R). The calculations involve five spatial scales: slopes (up to 0.0172 km²), the Tuanshangou Creek (Figure 1(c), 0.18 km²), the Chabagou Creek (Figure 1(b), 205 km²), the Dalihe River (Figure 1(a), 3906 km²), and the reach between station #21 and the confluence of the Yuxihe River into the Wudinghe River (Figure 1(a), 9355 km²), i.e. the IR#3 Reach in Table 1. The IR#3 Reach drains an area comprising the major part of the loess areas in the Wudinghe basin. The reach upstream of the IR#3 reach primarily passes through eolian sandy areas.

Table 2 presents all equations for calculating R_e , R_a , and R . On slopes, we used the observed sediment yield at longer plots as the sediment

Table 2 Calculations of R_e , R_a and R ^a

Site	R_e	R_a	R
Plot 2 ^b	SSY_{ep2} / SSY_{ep4}	SSY_{ap2} / SSY_{ap4}	SSY_{p2} / SSY_{p4}
Plot 3 ^b	SSY_{ep3} / SSY_{ep2}	SSY_{ap3} / SSY_{ap2}	SSY_{p3} / SSY_{p2}
Plot 7 ^b	SSY_{ep7} / SSY_{ep3}	SSY_{ap7} / SSY_{ap3}	SSY_{p7} / SSY_{p3}
Tuanshangou ^c	$\frac{SSY_{e3}}{\frac{1}{2}(SSY_{ep7} + SSY_{ep9})}$	$\frac{SSY_{a3}}{\frac{1}{2}(SSY_{ap7} + SSY_{ap9})}$	$\frac{SSY_3}{\frac{1}{2}(SSY_{p7} + SSY_{p9})}$
Chabagou ^c	- ^d	$SSY_{a9} / \frac{1}{4} \sum_{i=4}^7 SSY_{ai}$	$SSY_9 / \frac{1}{4} \sum_{i=4}^7 SSY_i$
Dalihe ^c	- ^d	$SSY_{a12} / \frac{1}{2} \sum_{i=10}^{11} SSY_{ai}$	$SSY_{12} / \frac{1}{2} \sum_{i=10}^{11} SSY_i$
IR#3 ^c	- ^d	$\frac{SSY_{a21}A_{21}}{(SSY_{a16}A_{16} + SSY_{a19}A_{19} + SSY_{a12}A_{IR\#3})}$	$\frac{SSY_{21}A_{21}}{(SSY_{16}A_{16} + SSY_{19}A_{19} + SSY_{12}A_{IR\#3})}$

Notes: ^a R_e , R_a and R represents the ratio between sediment output and sediment input at the event, annual and inter-annual timescales, respectively.

^b Plot length increases in an order of Plots 4, 2, 3 and 7 (Figure 1 (c)). SSY_{epi} and SSY_{api} represent the erosion intensity ($t\ km^{-2}$) at Plot i for a specific event and for a specific year, respectively. SSY_{pi} represent the mean annual erosion intensity ($t\ km^{-2}\ a^{-1}$) at Plot i for the period 1959-1969.

^c SSY_{ei} and SSY_{ai} represent areal sediment yield observed at station $\#i$ for a specific event and for a specific year ($t\ km^{-2}$), respectively. SSY_i represents areal sediment yield observed at station $\#i$ for the period 1959-1969 ($t\ km^{-2}\ a^{-1}$). A_{19} and A_{21} represent the drainage area upstream of stations $\#19$ and $\#21$, respectively. A_{16} represents the drainage area of the Yuxihe River (Figure 1(a)), and $A_{IR\#3}$ represents the drainage area between station $\#21$ and the confluence of the Yuxihe River into the Wudinghe River.

^d High spatially variability in rainfall prevents us from estimating R_e accurately when the basin size increases. Instead, we used the direct measurements of scour and fill along the stream channels in the Chabagou watershed (see Figure 4), and the temporal change of channel cross-section profiles of the Dalihe river and the Wudinghe river (see Figure 5), to evaluate whether downstream deposition occurs or not at the intra-annual timescale.

output, and that at shorter plots as the sediment input. Plots 7 and 9 are composed of two parts of hillslope and valley side slope. Such large-sized plots are termed as the entire slope in Chinese literatures. Permanent, incised gullies are developed at valley side slopes, allowing overland flows directly draining into the creek. Hence, we used observations at Plots 7 and 9 to calculate the sediment input into the Tuanshangou Creek. Comparisons of SSY_e of Plots 7 and 9 on the same rainfall day returns a linear equation with a regression coefficient close to 1 (0.94) and a R^2 of 0.93, indicating that SSY_e should be fairly uniform among entire slopes of the Tuanshangou sub-watershed. Hence, we believe that the sediment input into the creek can be effectively estimated using observations at Plots 7 and 9 though they only account for 12.7% of the whole drainage area of the Tuanshangou Creek.

For rivers, we used the sediment yield observed at the most downstream station as the

sediment output, and used the sediment yields observed at upstream stations plus that observed in tributaries to estimate the sediment input. We intentionally selected the tributaries in various parts of the river. Relatively small tributaries were excluded because they tend to be greatly affected by local extreme events. The total area upstream of the selected stations used for calculating the sediment input compose 42.8% and 37.7% of the total drainage areas of the Chabagou Creek and the Dalihe River, respectively. The upstream area of station $\#12$, the most downstream station of the Dalihe River, accounts for 41.6% of the drainage area of the IR#3 Reach. Hence, we directly used the observations at station $\#12$ as the sediment input per unit area from the tributaries into the IR#3 Reach. Physiographic properties, such as soil, topography, vegetation and the processes of erosion and sediment delivery, are fairly uniform in space over the hilly loess areas (Wang et al. 1982). Hence, we believe such estimations are reasonable

approximations.

In the Loess Plateau, rainstorms typically cover a small area of less than 10 km² (Zhang 1983). In this case, the observed difference in SSY_e may be simply a result of spatially uneven rainfall distribution. For this reason, we do not calculate R_e for the Chabagou Creek, the Dalihe River and the IR#3 Reach. Instead, we used the measurements of the channel morphology, including direct measurements of scour and fill and the temporal change of channel cross-section profiles, to evaluate the scour and fill at the intra-annual timescale. The measurements of scour and fill were made at six reaches within the Chabagou watershed. The reaches, four along the main stream and two along the tributaries of the Chabagou Creek (see Figure 1(b)), cover a length between 80 and 600 m (Table 3). The measurements along every reach were made at 5-14 cross sections with an interval between 20 and 50 m every one or several flood events. The height measurement was made using the level instrument

with a maximum allowed discrepancy between forward and backward levelling of $\pm 30 \sqrt{L}$ mm, where L (km) is the length of the levelled segment. By comparing with the last measurement, the depth of scour or fill at a cross section between two measurements was determined. The depth of scour or fill for a whole reach was then determined using the distance between the cross sections as the weight factor.

3 Results

3.1 The event or intra-annual timescale

As shown in Figure 2, R_e is larger than or close to 1 on slopes for major sediment-producing events ($SSY_e > 5000$ t km⁻²). R_e is significantly smaller than 1 only in case of small events. The same holds for the Tuanshangou Creek (Figure 3), suggesting that sediment deposition rarely occurs except during some small runoff events when moving

Table 3 Reaches under measurements of scour and fill

Reach Code ^a	Creek	Monitoring period	A ^b (km ²)	L ^b (m)	W ^b (m)	n ^b	d ^b (m)	Channel form
A	Chabagou	1963-1966	49	125	32	6	25	Sinuuous
B	Chabagou	1963-1966	96.1	200	64	5	50	Straight
C	Chabagou	1963-1966	151	600	106	14	46	Sinuuous
D	Chabagou	1963-1966	187	300	60	7	50	Straight
E	Tuoerxiang	1963-1966	5.74	80	22	5	20	Straight
F	Shejiagou	1963-1966	4.26	162	17	5	41	Straight

Notes: ^a The reach codes correspond to those given in Figure 1 (b).

^b A: Upstream area; L: length of the examined reach; W: Mean channel width; n: Number of the cross section under measurement; d: mean distance between two neighboring cross sections; $d = L/(n-1)$.

Figure 2 R_e on slopes, indicating whether downslope deposition occurs during runoff events (deposition occurs if $R_e < 1$).

Figure 3 R_e for the Tuanshangou Creek (0.18 km^2), indicating channel degradation or aggradation for single flood events (deposition occurs if $R_e < 1$). Three events had a markedly large R_e (> 3), so that they are presented using solid rhombuses with a given number representing the true value.

from slopes to the Tuanshangou Creek.

Figure 4 shows that single flood events, many of which had a SSY_e larger than $10,000 \text{ t km}^{-2}$, primarily cause a depth of scour or fill less than 5 cm whether along the tributaries or along the main stream of the Chabagou Creek. By contrast, our calculation shows that a 10% deposition loss would even lead to a net aggradation of 7.7 cm on average along the whole main stream of the Chabagou Creek in case of a moderate flood event having a SSY_e of 5000 t km^{-2} , given a mean channel width of 40 m (the channel width at the middle Chabagou Creek) and a specific weight of 1.4 g cm^{-3} for the deposition materials (Chien 1989). Hence, it can hardly be expected that significant channel scour or fill would accompany a single flood event in the 205 km^2 Chabagou watershed.

As shown in Figure 5, a similar observation holds for the Dalihe River and the Wudinghe River. A 10% deposition loss along the main stream of the Dalihe River would allow a net aggradation of 18 cm given a SSY_e of 5000 t km^{-2} (using the channel width in the middle reach, 50 m, to be the mean width). The equivalent value increases up to 50 cm for the IR#3 Reach of the Wudinghe River (using the channel width in the middle reach, 150 m, to be the mean width). In the context of

such a potential for enormous sediment storage, however, three cross-section profiles under examination, one of the Dalihe River (Figure 5(a)-(c)) and two of the Wudinghe River (Figure 5(d)-(h)), shows no signs of any deformation within a year. Both profiles of the Wudinghe River remained roughly unchanged before and after a flood season (May to September) even though the sediment yield over the flood season was up to 1.7 (Figure 5(g)) or 1.8 (Figure 5(e)) times as great as the long-term annual value. At the examined profile of the Dalihe River, channel aggradation only occurred during the flood event from Aug 27, 1967 to Sep 1, 1967 (Figure 5(c)), which recorded a SSY_e of 5675 t km^{-2} . Although the net aggradation

Figure 4 Depth of scour or fill relative to the last measure for (a) four reaches along the main stream, and (b) two reaches along the tributaries of the Chabagou Creek (205 km^2), indicating channel degradation or channel aggradation at the intra-annual timescale. The reach locations are presented in Figure 1(b). The first measurement generally occurred in June 1963.

Figure 5 Temporal changes of the channel cross-section profiles at stations of #12 (a)-(c), #20 (d)-(f), and #21 (g)-(h), indicating channel degradation or aggradation at the intra-annual timescale. The first and the last measurements are specially shown as lines for every year. The first measurement of the channel cross-section profiles generally occurred prior to a flood season, and the last occurred following the flood season. Areal sediment yield (in t km⁻²) and depth (in cm) of scour (-) and fill (+) between two measurements are presented. Note that for a clear presentation, the vertical scale is intentionally set larger than the horizontal scale in (d)-(h).

was nearly 50 cm, it was equivalent to a downstream deposition ratio of 21%. For two intra-annual periods recording a sediment yield higher than $10,000 \text{ t km}^{-2}$, channel degradation instead of channel aggradation occurred, with a scour depth of 39 cm (Figure 5 (b)) and 46 cm (Figure 5 (c)), respectively. Our calculations indicate that such degradations provided approximately 5% and 11% of the total sediment yield respectively, suggesting a very limited contribution by recruitment of sediment within stream channels.

3.2 The annual and inter-annual timescale

As mentioned in the introduction section, the annual sediment yield in the loess areas is typically dominated by a small number of large flood events. For instance, the maximum SSY_a value was as high as $71,100 \text{ t km}^{-2}$ at station #9 over the period 1959-1969. Although this value was about 3.3 times higher than the mean annual value, it was largely (about 95%) produced by four single events in 1966. Because R_e is generally larger than 1 for major

sediment-producing events, R_a remains larger than or close to 1 for major sediment-producing years ($SSY_a > 10,000 \text{ t km}^{-2}$; Figure 6). Measurements of cross-section profiles of stream channels of various orders also suggest very limited downstream sediment storage at the annual timescale. As shown in Figures 7 and 8, the six examined profiles varied little between neighboring pre-flood seasons over the years 1965-1970, with a depth of scour or fill primarily smaller than 10 cm.

The long-term sediment yield is largely determined by major sediment-producing years. Our calculation indicates that the major sediment-producing years contributed more than 90% of the total sediment yield at all examined sites other than Plots 4 and 2. As a result, R values we obtained are all larger than 1 from plots to watersheds (Figure 9). R values at the watershed scales, ranging from 1.05 to 1.12, are closer to 1 than R_a (Figure 6(b)); this observation indicates that the stream channels are in equilibrium between degradation and aggradation and the channel scour or fill has little effect on the long-term sediment yield.

Figure 6 R_a varying from slopes (a) to watersheds of various orders (b), indicating whether sediment deposition occurs at the annual timescale (deposition occurs if $R_a < 1$).

4 Discussion

Except for some small events ($SSY_e < 5000 \text{ t km}^{-2}$) or dry years ($SSY_a < 10,000 \text{ t km}^{-2}$), we do not find any evidence for sediment storage from plots up to the main stream of the Wudinghe basin; this suggests a SDR approaching 1 at the event or intra-annual timescale and at the annual timescale, not necessarily at the inter-annual timescale, as is commonly perceived.

Responding to larger runoff-contributing areas, erosion intensity increases in the downslope direction. As a result, R_e , R_a and R are typically larger than 1 on slope lands (Figure 2, Figure 6(a) and Figure 9). The field survey (Gong and Xiong 1979 and 1980; Xu and Sun 2004) consistently suggested no significant deposition loss on slopes in the Wudinghe basin; this considerable lends support to our results, which are simply based on observations within one among numerous sub-watersheds of the Wudinghe basin. The ^{137}Cs measurements (Jing et al. 1997) in other river basins of the Loess Plateau also agree well with our results.

Wang et al. (1982) and Xu (2004) reported a

Figure 7 Temporal changes in six cross-section profiles of stream channels of various orders in the Wudinghe basin. Note that all profiles were measured before flood seasons for ensuring comparability.

sediment storing-releasing mechanism in the Chabagou Watershed. During small flow events or the recession stage of rainstorm floods, flows are incapable of conveying the relatively coarse fractions of suspended sediment and deposit them in channels. The subsequent flows incorporate these deposited sediments and release them from

the channels. Both R_e in Figure 3 and R_a in Figure 6(b) falls within a narrow range for major sediment-producing events ($SSY_e > 5000 \text{ t km}^{-2}$) or years ($SSY_a > 10,000 \text{ t km}^{-2}$), averaging 1.2 when R_e or R_a is larger than 1; this implies that the pre-event sediment storage within channels contributes approximately 20% to SSY_e and SSY_a . The direct

measurements of scour and fill and the temporal change of channel cross-section profiles also do not suggest a remarkable channel scour whether at the intra-annual (Figures 4 and 5) or annual (Figures 7 and 8) timescale.

It is well known that SDR tends to be high where channel slopes and valley side slopes are steep (Goudie 2004; Diodato and Grauso 2009). In the Chabagou watershed, upland slopes are generally steeper than 36%. The channel slope decreases to 9%-18% for the smallest streams, and further decreases to 1.7%-3.5% for the tributaries and to 1.4% for the main stream of the Chabagou Creek. For the Dalihe River and the IR#3 Reach of the Wudinghe River, the channel slope is as gentle as 2.6‰ and 1.7‰, respectively. The fact that SDR remains close to 1 over a wide range of spatial scale and does not decrease with gentler channel can be related with hyper-concentrated flows. The fall velocity of sediment grains in hyper-concentrated flows is reduced by one (Pierson 2005) even two or three (Chien and Wan 1999) orders of magnitude relative to that in clear water. The calculation by Chien and Wan (1999) indicates that inclusion of additional sediment particles would not burden flows any more when sediment concentration exceeds 400 kg m^{-3} , a value much smaller than the mean sediment concentration of single events in the Chabagou watershed ($680\text{--}800 \text{ kg m}^{-3}$; see Table 4 in Zheng et al. (2012)).

As a result, hyper-concentrated flows have very strong capacity to carry sediment even in case of low flow strength. It has been well observed in the Loess Plateau that very high concentrations ($> 1000 \text{ kg m}^{-3}$) readily occur at extremely low discharges (See Figure 2 in Zheng et al. (2008)). Likewise, hyper-concentrated flows can travel a distance as long as 100-200 km (Chien et al. 1987; Chien 1989; Fei 1988), with little deposition loss and even the outline of sediment concentration hydrographs remaining almost unchanged (Fei 1988), regardless of the intensive backwater effect upstream of a reservoir (Chien et al. 1987) or the gentle channel gradient (0.2‰-0.25‰) (Fei 1988).

As shown in Figure 10, hyper-concentrated flows occur whether at low or at high discharges at station #12, where the channel gradient was as gentle as 0.25‰. Hyper-concentrated flows remain dominant in other first-order tributaries of the middle Yellow River, which has a channel gradient

Figure 8 Depth of scour of fill relative to the last pre-flood season at the six channel cross-section profiles. The measurement dates were given in Figure 7.

Figure 9 R varying from slopes to watersheds, indicating whether sediment deposition occurs at the inter-annual timescale (deposition occurs if $R < 1$).

Figure 10 The water discharge-sediment concentration relationship for the Suide station (#12). Data involve the period from 1959 to 1969.

between 1.5‰ and 8.9‰. These tributaries are thus likely to have a SDR close to 1 below the inter-annual timescale.

Sediment deposition on floodplains and other

sinks is strongly responsible for the decreasing SDR with increasing basin size (de Vente et al. 2007). In the Loess Plateau, floodplains are typically 1-2 meters in thickness and can rarely exceed a dozen of meters in width (Jing et al. 1993). Considering the long time period of the floodplains' development, the vertical accretion in one single year should be very limited (Jing et al. 1993), as demonstrated by Figures 7 and 8 and the field survey in the Wudinghe basin (Xu and Sun 2004). Terraces usually border the stream channel in the Wudinghe basin, but they are commonly at a considerable height above the present channel (above 2-3 m) so that the flood inundation rarely occurs. Alluvial fans at the river confluence are also not well developed (Xu and Sun 2004) and do not act as important sediment sink.

5 Conclusions

Information on the sediment delivery is scarce at the timescale below the inter-annual timescale, although it has been well known that SDR is close to 1 at the inter-annual timescale in the Chinese Loess Plateau. We evaluated sediment delivery from plots to watersheds at the event or intra-annual, annual, and inter-annual timescales, using observations at a series of nested sites within the 30,261 km² Wudinghe River basin during the period 1959-1969. It was found that sediment deposition rarely occurs except for some small runoff events (sediment yield < 5000 t km⁻²) or dry years (sediment yield < 10,000 t km⁻²) when moving from slopes to channels of various orders;

this suggests a SDR close to 1 at the event or annual timescale, but not necessarily at the inter-annual timescale. We do not find any significant channel degradation or aggradation at the spatio-temporal scales we examined. Such a high SDR can be related to hyper-concentrated flows, which are well developed in the Loess Plateau and can carry a large amount of sediment even at low flow discharges and at gentle channels.

Further work is needed to verify our inference at the event or intra-event timescale, because we only provided observations at three channel cross-section profiles when basin size is larger than 200 km². It is also desirable to investigate sediment delivery in other rivers of the Loess Plateau at various temporal scales, where hyper-concentrated flows dominate as well and promise to allow a SDR close to 1 at the event or intra-event timescale.

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