

## Study on Relation of Erosion and Sediment Yield in the Watershed System\*

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**Abstract:** Based on the observation data of erosion and sediment yield in the Dalihe Watershed, a important branch of Yellow River, the conclusion is brought forward that the erosion and sediment yield in the watershed system in a long-term time can reach balance, the sediment delivery ratio is approximate equal to 1; However, a great alteration range still exist in a short-term time like a different rainfall or a particular year, the sediment delivery ratio can reach more than 1 or less than 1 because the sediment in the watershed can be delayed or be transported again by runoff erosion. Sediment delivery ratio is close with runoff deep ratio, rainfall distributing and flood peak amplitude ratio in the watershed system. The characteristics of space-time distributing of delivery ratio in the various scales watershed and the influence factors to the delivery ratio in watershed systems are illustrated and some relative models are built in this paper.

**Keywords:** watershed system, erosion, sediment yield, sediment delivery ratio

### 1 Introduction

Since 1970, the mechanism of sediment delivery and the relation of the sediment yield and erosion were paid more attention in China. Gong *et al.* (1980) considered that average sediment delivery ratio in many years is about equal to 1, no matter larger or small watersheds in the hilly-gullied loess region of the Loess Plateau. Mu *et al.* (1982) has pointed out that sediment hyper-concentration flood is the major reason lead the sediment delivery ratio is 1 in this district, and Jing *et al.* (1997) appraised phenomenon on the opinion of geologic and geomorphology and analyzed the delivery ratio different law in different region basis on some qualitative index. For 10 near few years, Cai & Chen (1991) studied the relation of erosion and sediment yield in small watershed in the gullied-hilly loess region of the Loess Plateau, deemed that erosion and sediment yield are temporary disequilibria for a year and one time rainfall, the phenomenon that the silt can delay or carry existed in a short period in the gully bed. Zhang *et al.* (1994) also considered that the delivery ratio is a steady value in a certain watershed in long-term, and instability in short-term. Although such opinion have been accepted, but some serious problem still are not settled up to now such as the characteristic of temporal-spatial changes of erosion and sediment yield, the role of runoff affecting sediment delivery ratio in watershed system, the hydraulic ant landforms feature for delivery ratio combined influence with interaction, the different content flow carried silt influence to delivery ratio. The research on these problem is revealing and have important theoretical and practice meaning for exploring the sediment source of watershed system, the lay of erosion, transport and deposit and control methods of water and soil conservation.

### 2 Study region and methods

The study region encompasses the total area of Wudinghe watershed, covered 30,260km<sup>2</sup> area that can divide into three types including district of riverhead, the loess hilly-gullied and desert melt wind erosion, each type covered the 54.4%, 34.2% and 11.4% of the Wudinghe watershed area respectively. Dalihe river, is that the right bank second level tributary of middle reaches of Yellow River, is first level

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\* Doctor Fund offered by Southwest Agriculture University

tributary of Wudinghe river, locate in the hilly-gullied district of loess plateau, which area are affected by typical continental monsoon during June to September (Annual rainfall is about 450 mm), erosion modulus per year are about twenty thousands tons and covered by thick loess deposits, which consist of a layer of Malan Loess overlying much thicker Lishi Loess (> 50 m). the watersheds systematic physical geography general conditions are shown in Table 1.

Roehl's (1962) study have shown that the upland erosion can be estimated by an erosion model or extrapolated from measurements on small plots, and not equal to the sediment yield measured at the watershed outlet. To describe the differences, a sediment delivery ratio factor ( $Dr$ ) has been introduced as:

$$Dr = Y/A. \text{ Where: } Y \text{ is watershed sediment yield load; } A \text{ is upland erosion load.}$$

The gully watershed (small catchments) in loess area is the basic unit of erosion and sediment yield, in which the character of vegetations, lands use, landforms and erosion types have obvious comparability (Wang, 1982, Cheng, 1988, Lei & Tang, 1995), including each type of erosion (splash, rill, shallow, gully erosion, and gravity erosion) (Cai, 1998). According to the characteristic of erosion and sediment yield in loess hilly-gullied district, Mu, *et al.* (1982) considered that the small catchments unit (less than 1.0 km<sup>2</sup>) is sediment source in the Loess Plateau, and the sediment delivery ratio was defined as the small catchments erosion modulus divided with the watersheds scale sediment yield modulus. In this paper, the delivery ratio calculation is based on this definition.

**Table 1 Physical geography general situation of Dalihe river watershed system**

River name		Observation stations	Gully type	Drainage area (km <sup>2</sup> )	Drainage Density (m/km <sup>2</sup> )
Dalihe River	Chabagou river	Tuanshangou	Sublateral	0.18	
		Shejiagou	Branch	4.26	0.78
		Sanchuankou	Branch	21	0.79
		Xizhuang	Trunk	49	1.01
		Dujiagoucha	Trunk	96	1.06
		Caoping	Trunk	187	1.05
	Xiaolihe river	Lijiahe	Tributary of Dalihe	802	0.82
	Dalihe river	Suide	Outlet station of Dalihe	3893	0.88

### 3 Results and discussion

#### 3.1 Characteristics of temporal-spatial changes of the sediment delivery ratio

The average sediment delivery ratio in long-term is around 1 in a watershed system, and peak value appear in 50 km<sup>2</sup>—200 km<sup>2</sup> areas watershed system, according as the observation data in Dalihe watershed system (Table 2). If the area of the watershed is smaller of larger than 50 km<sup>2</sup>—200 km<sup>2</sup>, the sediment deposit will be raised.

**Table 2 Sediment delivery ratio averaged over years in Dalihe watershed system**

Profile	Drainage area (km <sup>2</sup> )	Drainage density (km • km <sup>-2</sup> )	Annual average Runoff depth (mm)	Sediment delivery ratio	Gully type
Tuanshangou	0.18			1	Sublateral
Shejiagou	4.26	0.78	55.6	0.83	Branch
Sanchuangou	21	0.79	52.3	0.75	Branch
Xizhuang	49	1.01	58.4	1.19	Trunk
Dujiagou	96.1	1.06	66.7	1.38	Trunk
Caoping	187	1.05	56.8	1.1	Trunk
Lijiahe	807	0.82	44.2	0.75	Tributary of Dalihe
Suide	3,893	0.88	50.2	0.89	Outlet station

Data covered years: 1961-1969; Drainage density from [Mu, 1982].

**Table 3 Sediment delivery ratio of different years in Dalihe watershed system**

Profile	Annual average rainfall (mm)			Annual average runoff depth (mm)			Sediment delivery ratio		
	1965	1966	1967	1965	1966	1967	1965	1966	1967
Shejiagou	192.9	458.3	468.9	26.7	114.6	58.1	0.164	0.82	0.96
Sanchuangou	212.2	460.6	481.9	26.6	96	43.6	3.1	0.73	0.76
Xizhuang	209.2	484.3	502.7	28.1	145.6	55.3	7.77	1.32	1.59
Dujiagou	215.7	484.7	507.6	29.2	143.7	70.3	17.67	1.27	2.03
Caoping	213.5	472.9	503.2	27	117.4	59.2	9.81	0.99	1.54
Lijiahe	164	350.3	466	22.1	63.9	50.9	6.79	0.46	1.32
Suide	192.8	423.1	497.2	23.4	56		8.74	0.35	

The Table 3 can show that the sediment delivery ratio is changed obviously with the range between 0.1—18 in different years, the following characteristics can be found:

(1) Variations of annual delivery ratio in a watershed system are related to variations of annual precipitation, annual runoff depth and gully density. Annual delivery ratio is consistence with annual delivery ratio averaged in many years in spatial distribution, and peak value exists in regions with watershed area ranging between 50km<sup>2</sup>—200 km<sup>2</sup>. The phenomenon of inter-annual and intra-annual retained sediments or sediments retained at initial stage that are re-eroded or transported again is generally found. The normal year (1966) peak value interval is close to value of multi-year average, and the declining magnitude increases apparently. Following the peak value interval, substantial amount of silt retained with the increase of drainage area and the retained silt can make up 65 % of the erosion amount. Comparison of dry year (1965) and abundant rain year (1966) reveals that following peak value interval, relative great delivery ratio can be formed with the increase of drainage area, the magnitude is great in low water year and smaller in high water year. The maximum annual sediment delivery ratio occurs in the dry year. In comparison of intra-annual runoff depth and the amount of precipitation, especially in terms of low water year with normal year and low water year, one can find that smaller runoff and runoff depth show greater delivery ratio. Therefore, changes in intra-annual sediment delivery ratio are irrelevant with annual precipitation and annual runoff depth.

(2) Annual delivery ratio is irrelevant with total annual sediment discharge, and the greater delivery ratio does not mean the greater sediment discharge. Take profile of Dujiacha as a case, in 1965 sediment delivery ratio was 17.67, sediment yield was  $36.51 \times 10^4$  t, whereas in 1966, sediment delivery ration was 1.27, and sediment yield reached  $877.4 \times 10^4$  t.

(3) Since changes in erosion induced sediment yield in a watershed are mainly related to several inter-annual rainstorm events, take the 8 runoff generated rainfall events in Tuanshangou in 1965 as a case, only one rainstorm event was recorded from flood observations at various profiles in Chabagou watershed, indicating sediment yield from a single rainstorm event only accounting for 23.9 % of the annual total amount. Inter annual local runoff generation predomination is beneficial to silt retaining, however, as flood forms throughout the watershed it is beneficial to the formation of greater delivery ratio.

**Table 4 Spatial-temporal change characteristics of sediment delivery ratio for single rainstorm event or annual rainfall**

Item		Watershed				
		Shejiagou	Sanchuangou	Xizhuang	Dujiagou	Caoping
Maximum	Year	2.09	3.79	6.9	16.78	9.32
	Time	3.97	10.09	6.4	6.89	9.29
Mean	Year	0.82	0.78	0.9	1.18	1.00
	Time	0.84	0.88	1.1	1.21	0.88
Minimum	Year	0.16	0.46	0.3	0.40	0.53
	Time	0.17	0.09	0.1	0.14	0.06

The Table 4 can show that in single rainfall event or different years the erosion and sediment yield didn't reach balance, but the average annual erosion and sediment yield in many years reach basically balance. Meanwhile, changes in annual sediment delivery ratio of single rainstorm averaged over years to single rainstorm as well as annual average sediment delivery ratio of various types of precipitation agreed in time-spatial changes. This shows that no matter changes in annual average or intra-annual delivery ratio, they are actually a synthetic embodiment of flood sediment delivery ratio from single rainstorm event.

### 3.2 Analysis of impacting factors

#### 3.2.1 Synthetic impact and interactions of geomorphic and fluvial dynamic characteristic indicators

According to analysis to observation data in Table 2, regression equation indicating synthetic impact of annual average runoff depth  $H$  (mm) and gully density  $G_m$  (km/km<sup>2</sup>) in Dalihe watershed system on annual average delivery ratio  $D_r$  can be given:

$$D_r = 0.031G_m^{1.08}H^{0.887} \quad r = 0.985 \quad (1)$$

Besides, a forecast model of annual average sediment delivery ratio of different watershed scales in Dalihe watershed impacted by hydrologic and geomorphologic characteristics can be built:

$$D_r = 0.657A^{-0.014}G_m^{0.962}H^{0.152} \quad r = 0.999 \quad (2)$$

In there  $A$  is drainage area (km<sup>2</sup>). In order to quantitatively analyses synthetic impact and interactions of hydrologic and geomorphologic characteristics under modern geomorphologic conditions on sediment delivery ratio, an optimum binary orthogonal multinomial regressive equation was obtained based on multinomial regressive analysis on changes of characteristic values determined by equation (2) and significant item maintained after  $F$  test:

$$D_r = 0.0033 - 0.00128H + 0.121G_m + 0.0188HG_m \quad (3)$$

Where deviation regression of various items in equation (3) all reaches a significant level of  $\alpha = 0.01$ .  $F$  testing values of  $H$ ,  $G_m$  and  $HG_m$  are respectively 49,396, 43,103 and 1,428, showing the impact of  $H$  on  $D_r$  has exceeded  $G_m$ , constituting an important factor that cannot be ignored in impacting long-term variations of sediment delivery ratio.

#### 3.2.2 Impact of a single rainstorm induced flood event

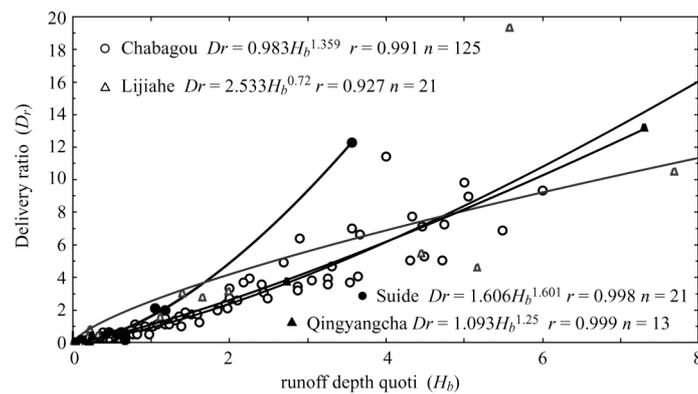
According to measurement data, runoff depth quotient ( $H_b$ ) in watershed system related to a single rainstorm generated flood and magnitude of peak flood increase quotient ( $H_f$ ) in gully system are closely related to pluviometric quotient ( $P_b$ ) (Table 5). In light with changes in rainfall induced sediment delivery ratio in Chabagou drainage system, runoff depth increase quotient and peak flood increase magnitude (Figures 1 and 2), as  $H_b > 1$ , runoff in per unit area in gully system increases, erosion capacity increases with increase of flow kinetic energy, sediment delivery ratio is greater than 1; as  $H_b < 1$ , per unit area runoff capacity decreases in drainage system, the increase in runoff loss due to infiltration and decay of kinetic energy is beneficial to silt retention, then sediment delivery rate is smaller than 1. When  $H_b \approx 1$ , rainfall is evenly distributed, erosion and sediment yield are liable to reach balance. Therefore, the increase ratio of a single rainfall induced runoff depth serves as per unit area flow kinetic energy characteristic indicator for determining whether erosion in watersheds of varying grades can reach balance with sediment yield. Fig. 2 shows the relationship of  $D_r$  and  $H_b$  under same rainstorm conditions in Lijiahe and Qingyangcha, the two trunk gullies of Dalihe River, and Suide and Tuanshangou of Wudinghe River. From the figure one can see the significant correlativity of  $H_b$  and  $D_r$  in watersheds of varying scales.

Changes in increase magnitude ratio of a single rainfall induced peak flood in Chabagou drainage system are also quite clear (Fig. 3). Sediment delivery ratio increases with the increase of peak flood increase magnitude quotient, when  $H_f$  is greater than a certain value; a threshold value of  $H_f$  impacting erosion and sediment yield balance also exists. Under conditions with same sediment delivery ratio, the larger the watershed, the increase magnitude quotient needed will be greater. When delivery ratio is equal to 1, a threshold of peak flood increase quotient can be reached, such as Shejiagou is around 10, Sanchuankou increases to around 30, and Caoping increases to about 80. When the above-mentioned peak flood increase quotient in the drainage system reaches threshold, the balance between erosion and sediment yield will be

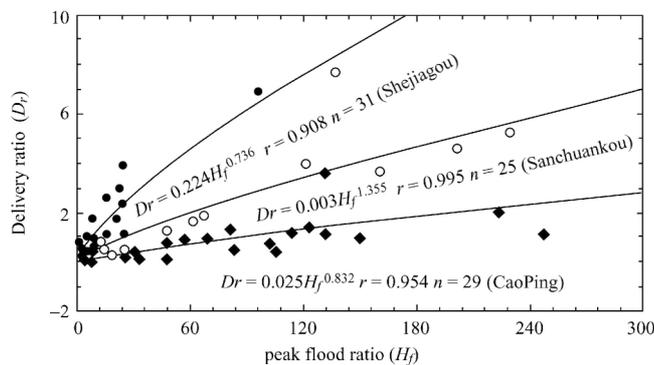
resulted. When delivery ratio is 1, smaller than threshold is deposition, and greater than threshold is scouring. The larger the drainage area, the rate of increasing peak flood magnitude ration would be smaller.

**Table 5** Relations between  $H_b$  and  $H_f$  with  $P_b$

Profile	Equation	Correlative coefficient ( $r$ )	No. of sample ( $n$ )
Shejiagou	$H_b = 1/(1.89-1.09P_b)$	0.655	31
	$H_f = P_b/(0.179-0.109P_b)$	0.699	
Sanchuankou	$H_b = 1/(1.086-0.344P_b)$	0.715	25
	$H_f = 1/(0.037-0.01P_b)$	0.713	
Xizhuang	$H_b = P_b/(1.37-0.616P_b)$	0.853	18
	$H_f = P_b/(1.345-0.216P_b)$	0.971	
Dujiagou	$H_b = P_b/(0.511-0.015P_b)$	0.631	20
	$H_f = P_b/(0.01-0.001P_b)$	0.619	
Suide	$H_b = P_b/(0.907-0.342P_b)$	0.698	29
	$H_f = 1/(0.019-0.012P_b)$	0.728	



**Fig. 1** Relationship between runoff depth quotient ( $H_b$ ) and delivery ratio ( $D_r$ ) for a single rainfall event



**Fig. 2** Relationship between delivery ratio  $D_r$  and change magnitude of peak flood ratio  $H_f$

Of the 8 runoff generating rainfall in 1965 in Tuanshangou, only one event resulted in flood on all profiles in Chabagou, a single event rainstorm yielded sediment volume only accounted for 23.9 % of the

years total. The remaining 7 rainfall events generated runoff locally, which clearly reflected the changes in erosion and sediment yield in 1965 from direct receiving unit Wangjiagou station where delivery ratio was only 0.164. Based on regressive analysis, it is possible to gain prediction model, which described the synthetic impact of the rainfall-generated runoff in Chabagou drainage system of Dalihe River in the loess hilly-gully areas on sediment delivery ratio:

$$D_r = 0.403P_b^{0.37} H_b^{1.066} H_f^{0.191}, \quad r = 0.996, \quad n = 125 \quad (4)$$

The transformation relationship of a single rainfall related sediment delivery ratio with erosion amount and sediment yield can be given from the following expression:

$$T = Y / D_r \quad (5)$$

In there  $T$  is single rainfall induced sediment delivery ratio,  $Y$  is the amount of erosion, and  $D_r$  refers to sediment yield.

### 3.2.3 Impact of flow silt carrying capacity

Under single rainfall conditions, the silt-carrying capacity in different I grades drainages can be made out by the calculation equation below:

$$H_n = H_{so} - H_{si} \quad (6)$$

In there  $H_n$  denotes per unit runoff volume increment of silt yield ( $\text{kg}/\text{m}^3$ );  $H_{so}$  is average silt content delivered from various grades of gullies ( $\text{kg}/\text{m}^3$ );  $H_{si}$  is average silt content delivered from small unit gully drainage ( $\text{kg}/\text{m}^3$ ). Measurement data indicated that changes in silt-laden capacity of gully runoff are close to runoff increase or decrease in per unit area (Fig. 3), therefore, sediment delivery ratio of drainage system is close to the rise or fall of silt-laden capacity of the gullies, and scouring and siltation of the gully beds (Table 6). It is very clear that when kinetic energy of silt-laden runoff increases, both silt carrying capacity and silt yield increases, hence sediment delivery ratio is greater than 1; when silt carrying capacity in these drainage systems is equal to that of unit small catchments, delivery ratio is 0; when kinetic energy weakens, silt is liable to deposit, delivery ratio is smaller than 1.

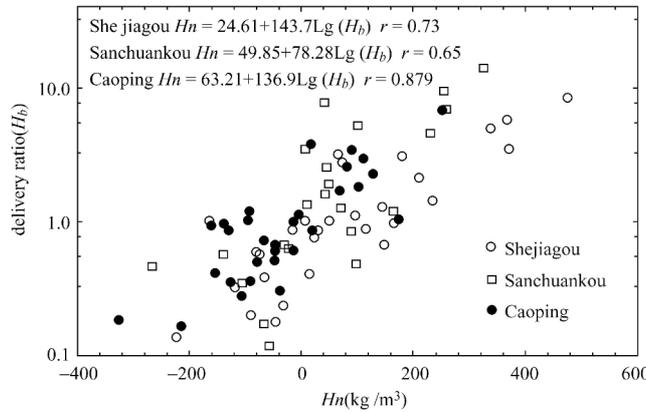


Fig. 3 Relationship between runoff depth  $H_b$  and silt content increment  $H_n$

Table 6 Equations indicating relationship between runoff depth  $H_b$  and silt content increment  $H_n$

Station	Equation	Correlative coefficient (/r)	No. of sample (/n)
Shejiagou	$H_n = -25.71 + 92.8 \lg D_r$	0.76	31
Sanchuankou	$H_n = 29.58 + 67.0 \lg D_r$	0.688	23
Xizhuang	$H_n = 61.002 + 122.1 \lg D_r$	0.73	19
Dujiagou	$H_n = 61.7 + 93.59 \lg D_r$	0.777	20
Caoping	$H_n = 58.64 + 114.89 \lg D_r$	0.917	30

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