◆Research Paper◆

Study on the Phase Characteristics of the Collocation Relationship Between Runoff and Sediment in the Slop-Gully System

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Abstract: Slope-gully system is the basic unit to study the erosion regularity and arrange the soil and water conservation measures. The study on the phase characteristics of the collocation relationship between runoff and sediment is very important for arranging soil and water conservation measures of adaptation to local condition. Based on the Key Laboratory of Yellow River Sediment Research of Ministry of Water Resources, the paper analyzed the process of runoff and sediment production in the slop-gully system of the soil erosion and the phase characteristics of the collocation relationship between runoff and sediment in the 3 different rainfall intensities by using the artificial rainfall simulation test method. The results showed that:
(1)Under the condition of a certain underlying surface, there is a critical point in the process of soil erosion in the slope-gully system. Less than the certain rainfall intensity, the runoff and sediment yield increased greatly with the increasing rainfall intensity. Over the certain rainfall intensity, the increasing degree of runoff and sediment yield and the velocity of erosion evolution slowed down.
(2) The rainfall intensity and rainfall are important factors for affecting the process of erosion and sediment yield. And the effect of rainfall intensity on runoff and sediment yield is even greater than the rainfall.
(3)The collocation relationship between the runoff and sediment in the slop-gully system of the quasi shallow gully erosion stage was significantly different from that of sheet erosion stage and rill erosion stage. And with the same runoff yield, sediment yield increased significantly. Therefore, the soil and water conservation measures should be arranged according to the erosion development stage and the rainfall characteristics.

Key words: slop-gully system， runoff and sediment yield，the collocation relationship between the runoff and sediment，phase characteristics

1 Introduction

The surface soil on slope would be stripped away from the original surface by the rainfall runoff, which ends up with soil and water loss. Soil and water loss not only caused the ecological environment deterioration and declining agricultural productivity, but also seriously restricting the sustainable development of social economy. Slope-gully system is the main source of erosion sediment in small watershed, and it's also the basic unit to control soil erosion, restore and reconstruct ecological environment. The erosion process and mechanism research can not only provides scientific basis for arranging soil and water conservation measures, but also has important significance for the restoration and reconstruction of ecological environment.

The study on the relationship between rainfall and sediment yield of slope-gully system originated from the debate about the key controlling region in 1950s, which reflects the weakness of soil erosion researching. With the constant development of soil erosion process, people gradually realized that slope and gully is an indivisible whole in the soil erosion process(Chen,1993, Chen et al.,1999). And the study of soil erosion mechanism has obtained high-quality results(Wei et al.,2010, Xiao et al.,2009, Ding et al.,2005, Yao et al.,2011, Xiao et al.,2007, Wei et al.,2012). Xiao PeiQing et al.(2009)quantitatively analysised the characteristics of slope runoff and hydraulic parameters in slope-gully system by means of rainfall simulation. They pointed out that with the increasing rainfall intensity, the runoff changed from the slow flow into the rapids, runoff Reynolds number and Froude number increased markedly, the Darcy-Weibach decreases, and the sediment yield was significantly increased eventually.Wei Xia et al.(2010) studied the erosion process of slope-gully system by artificial water scoured experiment and showed that the runoff and sediment yield increased exponentially with the growth of water inflow rates.

During the transformation process of sediment stripped away from the original surface by the rainfall runoff, runoff and sediment yield were constantly changing. But during the process of soil erosion in the slope-gully system, the collection relationship between the runoff and sediment has a certain phase characteristics. In the existing research results, the qualitative and quantitative research about this field is rare, which is not conducive to arrange the water and soil conservation measures. For that reason, in this paper, the phase characteristics of runoff and sediment yield in slope-gully system are studied quantitatively and qualitatively through the artificial rainfall simulation method.

2 Material and methods

The experiment was conducted in the Key Laboratory of Yellow River Sediment Research of Ministry of Water Resources. According to the actual situation of the Loess Plateau and the laboratory's facilities, the experimental soil box of slope-gully system was designed, as shown in Figure 1. The experimental model is composed of two parts (the slope and gully slope), which is 10 meters in length, 1 meters in width. Based on the previous research results and the investigation of the degrees of hill slope and gully slope, determined the degrees of hill slope and gully slope(20° and 35°). As for the geometrical features of the model, it's projection area are 9.60m^2, and it's total height is 4.59m.

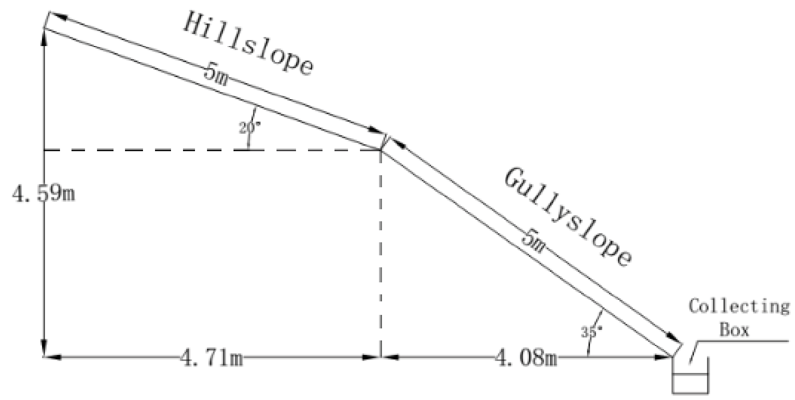

Fig.1 Sketch map of experimental soil bed of slope-gully system

The soil material used in this study is the loess from Mangshan Mountain located at the north of Zhengzhou City, Henan Province, China. This paper sifted them through sieves with 5 mm aperture first, and then layered and patted strictly into the soil box. The depth of fill was 45cm. And the Soil bulk density was controlled in 1.22~1.25g/cm^3. After filling, the soil was made to reach the saturation state through a drizzle initiated by artificial rain, and then natural settling for 24h in order to control the soil moisture content in 14%~15%, which can eliminate the influence of different water content in the early stage. The percentage of the soil grain size is shown in Table 1.

Table 1 The percentage of the soil grain size

Grain size/mm	1.0	1.0-0.25	0.25-0.05	0.05-0.01	0.01-0.005	0.005-0.001	<0.001
percentage/%	0	1.05	34.45	43.40	3.20	6.40	10.50

The rainfall equipment used in the experiment is the automatic artificial rainfall system of the test chamber. The rainfall system (TSJY-1) is composed of sprinkler, pressure pipe, water system, etc. Through setting the nozzle size, the length of time, pressure and other parameters on the visual interface of the rain water system in the control room, can simulate different rainfall intensity and rainfall duration. The height of nozzle is 22m, can ensure that more than 95% of the rain drops reach to the uniform fall state, which has a high degree of similarity with the natural environment. In this experiment, the rain intensity (66mm/h, 42mm/h, 85mm/h) were determined by parameters setting and direct measuring, and the uniformity of rainfall was 85%, 89.5% and 86.8% respectively. Parameter setting of rainfall simulation system is shown in table 2.

Table 2 Parameter setting of rainfall simulation system

Rainfall intensity (mm/h)	Nozzle	Pressure (Pa)	Rainfall duration (min)	Uniformity (%)
42	5#	0.1	140	85
66	5#	0.2	100	89.5
85	4#	0.04	62	86.8

During the experiment, the critical time that runoff and sediment beginning were recorded， and all the runoff and sediment samples were collected every two minutes using a big bucket. In the course of the experiments, monitored dynamically the width and depth of the gully of slope-gully system by the thin steel ruler and digital camera. After the experiment, weighed the runoff and sediment quality, and determined the runoff volume, and finally calculated the runoff and sediment yield data by the replacement method.

3 Results and discussion

3.1 The process of runoff and sediment yield in slope gully system

In this artificial rainfall simulation tests, 142.5min after the rainfall, intensity 45mm/h, the slope in the model was scoured out many small ditch whose depth was less than 3cm by the dispersive small runoff, or appeared surface layer of soil loss, and the process of gully development was slow. As for 65mm/h and 85mm/h, 100min and 62min after rainfall, respectively, the slope was scoured out many shallow grooves whose depth was about 15cm by the big runoff collected from the dispersive small runoff, and the gully slope was constantly washed lead to collapse of the local soil. Therefore, the rainfall intensity was stronger, the rainfall duration was shorter, the gully development in the soil erosion process of slope-gully system was faster, and the surface land was incised more fiercely.

According to the test record, the initial runoff time of 42mm/h, 66mm/h, 85mm/h was 2.5min, 2min, 1min, respectively, which proved that the initial runoff time of high rainfall intensity was earlier than the low rainfall intensity. It means that the rain was infiltrated and absorbed by soil for the reason that the initial infiltration capacity of soil was greater than that of rainfall intensity at first. With the rainfall, soil infiltration capacity decreased with the increased of soil water content. When the soil infiltration capacity was less than the rainfall intensity, the slope-gully system started to flow.

With the generation of surface runoff, the sand of slope-gully erosion was output. The process curve graph of runoff and sediment yield in 3 kinds of rainfall intensity is plotted according to the runoff and sediment sample data (figure 2, figure 3). From the figure we can found that the effect of rainfall intensity on runoff and sediment yield of slope gully system was very obvious. The process curve of rainfall runoff and sediment yield of 42mm/h was significantly lower than that of 66mm/h and 85mm/h. Under the same rainfall condition, the increasing trend of runoff yield with the runoff time was greater than that of sediment yield with the increase of runoff time, which was consistent with the relationship between runoff and sediment yield in slope-gully system ($y=ax^b$) based on rainfall simulation experiments by Xiao Peiqing et al.(2007).

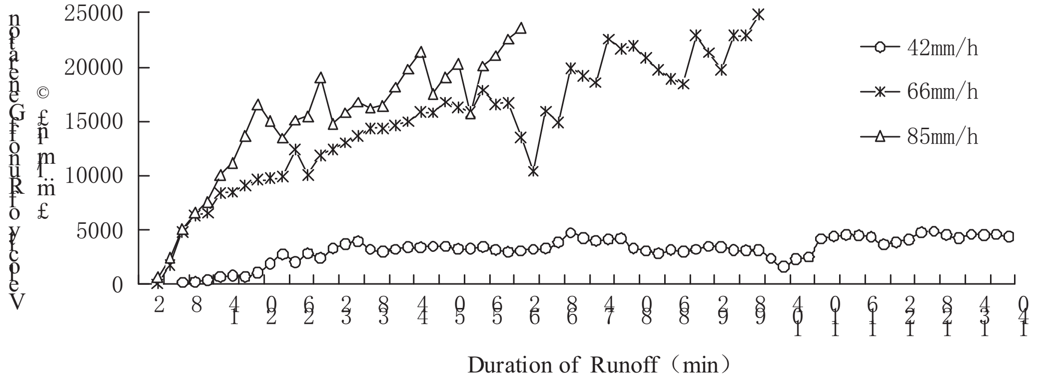

Fig 2 The process of runoff of 3 kinds of rainfall intensity

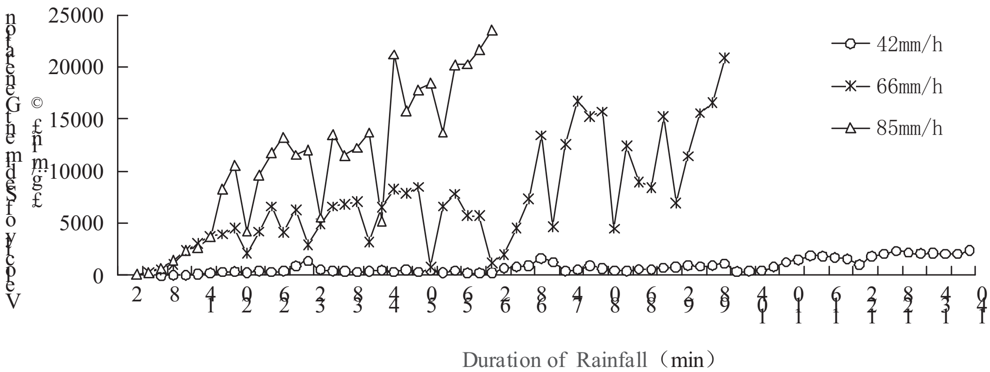

Fig 3 The process of sediment yield of 3 kinds of rainfall intensity

20min after rainfall, with the formation of overland runoff in the slope-gully system, the water content of the soil reached saturation state, and soil infiltration rate tended to be stable. Based on the above reasons, the difference of later runoff process was caused by rain intensity. Under the premise of same rainfall duration, compared with the rainfall intensity of 42mm/h, the rainfall intensity of 66mm/h is 1.57 times as high as that of 42mm/h, but the cumulative runoff and sediment yield of 66mm/h is respectively 5.20 times and 14.76 times as much as that of 42mm/h; the rainfall intensity of 85mm/h is 2.02 times as high as that of 42mm/h, but the cumulative runoff and sediment yield of 85mm/h is respectively 6.27 times and 36.27 times as much as that of 42mm/h. Compared with the rain intensity of 66mm/h, the increasing degree of rainfall intensity of 85mm/h was about same as that of cumulative runoff and sediment yield (Rain intensity increased by 0.29 times, and the cumulative runoff and sediment yield increased respectively by 0.31 and 2.27 times). These analytical data showed that, with the increase of rainfall intensity, the cumulative runoff and sediment yield had the trendency of accelerates increase, but when rainfall reaches a certain intensity, the trend of cumulative runoff and sediment yield increased with the increasing rainfall intensity would weaken.

3.2 The phase characteristics of runoff and sediment yield in slope-gully system

In the time scale, the development period of soil erosion in slope-gully system were different under the different rainfall conditions. The soil erosion process in slope-gully system was divided into surface erosion stage (before rill formation), rill erosion stage (rill formation to fine deep groove width within 20cm) and quasi shallow channel (Yao et al. 2011) erosion stage (deep gully erosion stage were greater than 20cm) under the experimental conditions. These erosion forms appeared in succession and usually concomitantly exist in erosion development process of slope-gully system. The time of next erosion forms appeared and became the main erosion forms in the erosion process would be regarded as the boundary between different erosion stages. The process curve graph of runoff and sediment yield in 3 kinds of rainfall intensity and the record data from the soil erosion process observation were combined to analysis the phase characteristics of runoff and sediment yield in slope-gully system (table 3). Under the condition that the rain intensity was 42mm/h, the whole development process of soil erosion was divided into surface erosion and rill erosion stage, and didn’t reach the quasi shallow gully erosion stage. But under the condition that the rain intensity was 66mm/h and 85mm/h, the soil erosion developed to the quasi shallow gully erosion stage, and the stronger the rain intensity, the earlier the erosion stage occurred. For the same erosion stage, the velocity of runoff and sediment generation and the average sediment concentration in runoff increased with the increasing rain intensity and the development of erosion stage. It can be seen that the rainfall intensity and rainfall are the important factors that affect the process of erosion and sediment yield.

Table 3 Phase characteristics of runoff and sediment yield in slope-gully system

Item	Stage	42mm/h	66mm/h	85mm/h
Duration	surface erosion	0~40	0~24	0~16
(min)	rill erosion	40~140	24~60	16~40

	quasi shallow gully erosion		60~100	40~62
Velocity of runoff generation (ml/min)	surface erosion	1983	6246	6831
	rill erosion	3666	14650	15710
	quasi shallow gully erosion		19566	19951
Velocity of sediment generation (g/min)	surface erosion	376	1627	2592
	rill erosion	1027	5921	10357
	quasi shallow gully erosion		10727	17423
Average sediment concentration in runoff (g/ml)	surface erosion	0.18	0.22	0.32
	rill erosion	0.26	0.41	0.66
	quasi shallow gully erosion		0.52	0.87

Runoff and sediment yield were the result of the combined effects of rainfall and rain, but the two showed the different effect on runoff and sediment yield. The regression analysis of cumulative rainfall (P) of each stage and the corresponding rainfall intensity (I) derived that an inequality had to be met in the relationship of the velocity of sediment generation (Sq), velocity of runoff generation (Wq) and the accumulated rainfall (P) , rainfall intensity (I) :

$$S_q = 108.32P + 238.65I - 16474.1 \quad (R=0.7854) \tag{1}$$

$$W_q = 135.46P + 281.81I - 16232.6 \quad (R=0.8178) \tag{2}$$

From the regression coefficient of formula (1) and (2), it could be found that the effect of rain intensity on velocity of runoff generation was 2.1 times as much as that of rainfall, and the effect of rain intensity on velocity of sediment generation was 2.2 times as much as that of rainfall. This suggested that the effect of rainfall intensity on velocity of runoff and sediment generation was stronger than rainfall. The results were consistent with the conclusion of Wei Wei et al. (2012) - rain intensity is the most major factor affecting soil and water loss in all characteristic value of rainfall.

3.3 The collocation relationship of runoff and sediment yield in different erosion stage

The law of collocation relationship of runoff and sediment yield is a very complicated problem, and that is different in different erosion stages. Under different rainfall conditions, the relationship of runoff and sediment yield in the slope-gully system at different erosion stages is shown in Fig 4.

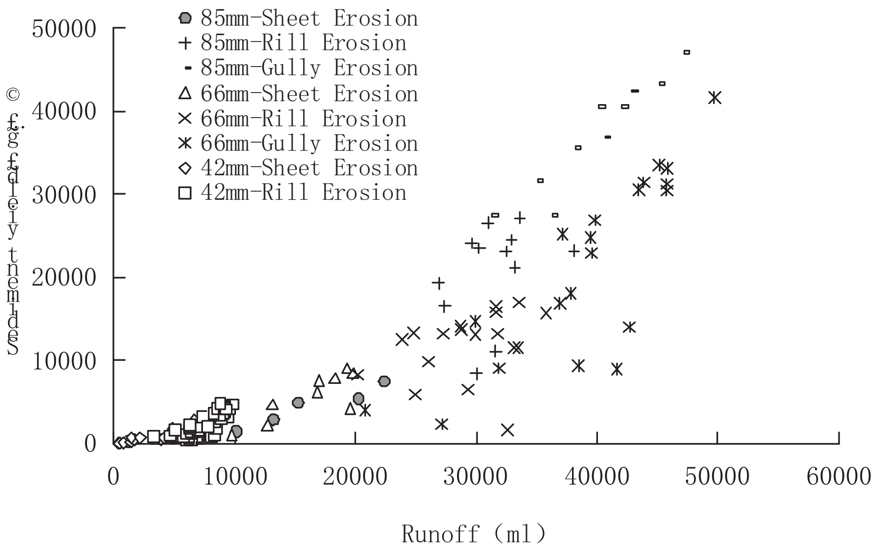

Fig 4 The scatter diagram of runoff and sediment yield at different erosion stages

Further analysis the distribution characteristic of the data points in figure 4, in the sheet erosion stage, the collocation relations of runoff and sediment yield under the 3 kinds of rain intensity condition were basically the same, which satisfied the formula $y=ax^b$ (y is the sediment yield, and x is runoff); In the rill erosion stage, the runoff and sediment yield data of 85mm/h is slightly higher than that of 66mm/h, but still satisfied the above formula; when the erosion developed to the quasi shallow gully erosion stage, the collocation relations of runoff and sediment yield under the 2 kinds of rain intensity condition tended to satisfying the linear relationship which is y=ax+b (x, y ditto). It specifically demonstrated that under the condition of same volume of runoff, the stronger the rain intensity, the higher the content of the sediment (see Table 4).

Table 4 The collocation relationship of runoff and sediment yield in different erosion stage

Erosion	Rainfall intensity (mm/h)	Formula	Correlation coefficent	Sample number
Surface erosion	42、66、85	$y = 0.0028x^{1.4806}$	0.934	34
Rill erosion	42、66、85	$y = 0.0021x^{1.5279}$	0.901	80
Quasi shallow gully erosion	66	$y = 1.2776x - 28544$	0.818	20
	85	$y = 1.3323x - 15879$	0.948	11

4 Conclusions

(1)With the increase of rainfall intensity, the cumulative runoff and sediment yield had the trend of accelerates increase, but when rainfall reached a certain intensity, the trend of cumulative runoff and sediment yield increased with the increasing rainfall intensity would be weaken.
(2)Under the conditions of same underlying surface, the stronger the rain intensity, the earlier the erosion stage occurred. For the same erosion stage, the velocity of runoff and sediment generation and the average sediment concentration in runoff increased with the increasing rain intensity and the development of erosion stage. Rainfall and rainfall intensity are the important factors that affect the process of erosion and sediment yield, and the effect of rainfall intensity on velocity of runoff and sediment generation was stronger.
(3)The relationship of runoff and sediment yield was different in different erosion stages. In the quasi shallow gully erosion stage, under the condition of same volume of runoff, the stronger the rain intensity, the higher the content of the sediment.

5 References

[1]Chen Hao. Study on sediment yield in Watershed slope and Gully. Bei Jing: China Meteorological Press, 1993
[2]Chen Hao, Wang Kaizhang. Study on the relationship of slope gully erosion in small watershed in the middle reaches of the Yellow River River. Geographic Research, 1999,18 (4)：363-372
[3]Wei Xia, Li Xungui, Li Zhanbin. Runoff and sediment process in the Loess Plateau. Journal of Lanzhou University, 2010，46 (5)：7-10
[4]Xiao Peiqing, Zheng Fenli, Yao Wenyi. Study on characteristics of runoff and hydraulic parameters of slope gully system. Advances in Water Science, 2009，20(2)：236-240
[5]Xiao Peiqing, Zheng Fenli, Yao Wenyi. Study on the relationship between runoff and sediment yield in slope gully system. Journal of Sediment Research, 2007 (2) :30-35
[6]Yao Wenyi. Biological and geological processes of soil erosion and its driving mechanism (2007CB407201). Summary report of the national key basic research and development plan. The Yellow River Research Institute of water conservancy, August 2011.
[7]Wei Wei, Chen Liding, Yang Lei et al,. Multi-scale responses of soil erosion process to rainfall and underlying factors. Academic papers on natural geography and ecological security. Natural geographical exhibition industry committee of

China Geographic Society. Lanzhou, 2012

[8]Ding Wenfeng, Li Mian, Yao Wenyi et al,. Experimental study on the coupling relationship between erosion and sediment yield in slope gully system. The sixth session of the national basic theory of sediment, Zhengzhou: yellow River Conservancy press, 2005，122-128