

## **Effects of Up-Slope Runoff on Erosion Processes At Down-Slope Shallow Gully Erosion Areas**

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### **ABSTRACT**

Shallow gully erosion (like ephemeral gully erosion) is a special erosion type formed by erosion processes and plough activities, and it causes severe soil loss at steep hillslopes. Field investigation showed that up-slope runoff had a great impact on erosion process at down-slope shallow gully erosion dominated area in the Loess Plateau of China. However, because of complex field conditions, it is difficult to identify quantitatively how up-slope runoff affects down-slope shallow gully erosion process under different rainfall, runoff, and surface conditions. A dual-box system with a 1.5m wide by 2m long feeder box and a 1.5m wide by 3m test box was conducted to study effects of up-slope runoff on erosion processes at down-slope shallow gully erosion area under 36.4 % slope gradient and 50, 70 and 90 mm h<sup>-1</sup> rainfall intensities. The researched results demonstrated that under experimental conditions, sediment regimes were always detachment-transport dominated at steep hillslopes with shallow gully landscape. The additional sediment detachment at a down-slope shallow gully area caused by the up-slope runoff increased with a decrease of sediment concentration in up-slope runoff or an increase of rainfall intensity. Meanwhile, the sediment delivery during the run was associated with active shallow gully head-cut advance. An increase of shallow gully flow velocity after up-slope runoff discharging into down-slope section was a key reason of sediment delivery increase in the down-slope section. In a rainfall event, the sediment delivery at the down-slope was dominated by erosion amount of shallow gully channel where single shallow gully rapidly developed. These findings will help to improve the understanding of shallow gully erosion processes.

### **INTRODUCTION**

Shallow gully (like ephemeral gully), formed by erosion processes and plough activities (Zhu, 1956), are wider and deeper than rills, but they can be tilled across and filled in partially or completely (Hutchinson and Pritchard, 1976). Shallow gully erosion is referred to as concentrated-flow erosion, or mega-rill erosion, and it causes severe soil loss at steep hillslopes. In the United States, ephemeral gully erosion contributed from 17 % of total soil loss at New York State to 73 % at Washington State (USDA-NRCS, 1977); in the loessial belt of Europe, ephemeral gully erosion

contributes at least 10 % of the total loss (Robinson et al., 1998). In the hilly-gully region of the Loess Plateau, the shallow gully erosion amount takes up above 60 % of total soil loss at steep hillslopes. Therefore, understanding of shallow gully erosion process is important for erosion modeling and controlling.

Recent field observation in the Loess Plateau showed that runoff from up-slope areas resulted in additional sediment delivery at down-slope shallow gully erosion dominated area, and the additional sediment was reduced with an increase of sediment concentration in runoff from up-slope (Zheng, 1997; Zheng et al., 2000). Since field conditions are complex, and it is difficult to identify quantitatively how runoff and sediment from up-slope area affects sediment delivery and transport at down-slope shallow gully section under different rainfall, runoff, and surface conditions.

Recently, the dual-box system, consisting of an up-slope feeder box and a down-slope test box, provides a good way of identifying quantitatively how runoff and sediment from up-slope areas affect down-slope erosion processes (Huang et al., 1999). Huang et al. (1999) and Zheng et al. (2000) used the dual-box system to study effects of run-on water and sediment on erosion processes and sediment regimes at down-slope section without shallow gully landscape. Their research results showed under a 10 % slope and free drainage condition, the runoff from the feeder box caused additional sediment delivery in the test box, indicating a transport-dominated sediment regime. In the gentle slope (5 and 10 % slope) and steep slope (36.4%) without shallow gully landscape, sediment delivery, erosion processes and sediment regimes can be changed by sediment concentration in up-slope runoff, rainfall intensity, and surface conditions (Huang et al, 1999; Zheng et al, 2000).

Motivated by previous field observations in China and the capability of a dual-box system to simulate hillslope erosion processes, we designed a laboratory study to quantify the up-slope runoff and sediment effects on erosion processes at down-slope shallow gully dominated erosion area under different rainfall intensities. During the experiment, the sediment concentration from the feeder box was varied, while maintaining a constant level of runoff, to create a range of up-slope boundary conditions for the test box. The subsequent response of the test box can be used to evaluate the erosion process. Results of this study will further the understanding of shallow gully erosion process.

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## MATERIALS AND METHODS

### Soil Sample Collection

The soil used in this study was clayey loess collected from Yangling Town, Shaanxi province, China. The soil was sampled from a very deep soil layer (6-m deep) of farmland, which layer would be C-Horizon. A sufficient amount of soil was transported back to the laboratory for the experiments.

### Experimental Setup

The simulated rainfall experiments were done in the simulation hall of Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resource, China. The study was conducted on a dual-box system consisting of a 3-m long test box and a 2-m long feeder box with 36.4 % slope. Both boxes were 1.5-m wide. These two boxes can be connected by the connecting piece to feed the runoff from the feeder box into the upper-end of the test box. When these two boxes disconnected, runoff samples can be collected separately from each box. The connection and disconnection can be done quickly without stopping the rain.

For both soil boxes, the depth of soil was approximately 50 cm with a 2-cm layer of sand at the bottom. These two boxes were placed under two simulators with side-nozzle (Chen et al., 1984). The height of raindrops falling was 16 m, the designed rainfall intensities were 50, 70, and 90 mm h<sup>-1</sup>, average raindrop diameter was 0.98, 1.14 and 1.18 mm, respectively.

### Soil Box Preparation

Preparation of soil boxes included removing soil from these two soil boxes and parking soil boxes with fresh air-dried soil, and smoothing out the visual irregularities on the surface by hand and with a rake. In addition, in order to study up-slope runoff effects on shallow gully erosion, an initial shallow gully shape was made in the test box according to measurement data from contour map, and feed box was straight slope before pre-rain. These two soil boxes were packed in 5-cm layers to ensure uniform density. Soil bulk density was 1.12 to 1.15 g cm<sup>-3</sup>.

### Pre-rain

Once the boxes were prepared, a 10 min rainfall of 30 mm h<sup>-1</sup> was applied one day before run, and no any runoff occurred at soil box surface. The pre-rain was to reduce surface variability from preparation. Before making run, soil water content was measured. For the all treatments, soil water content was 25 to 26%.

### Experimental Procedure

Both boxes of the test box and feeder box was set to the selected rainfall intensity (Table 1). The sediment concentration in the feeder box was varied by progressively covering portions of the surface with plastic sheet that prevented direct raindrop impact to create same runoff with different sediment concentration during each run.

The run started with 0% cover on the feeder box, thus the highest level of sediment production. Runoff samples from

Table 1. List of experimental treatments.

Treatment	2-m Feeder Box			3-m Test Box	
	Slope %	Rainfall mm/h	Cover %	Slope %	Rainfall mm/h
1*	36.4	50	0; 25;50; 75; 100	36.4	50
2	36.4	70	0; 25;50; 75; 100	36.4	70
3	36.4	90	0; 25;50; 75; 100	36.4	90

\* Each run was replications twice.

both boxes were collected in 1-liter plastic bottle every minute. After collecting 8 runoff samples from each box separately, the two boxes were connected to let the runoff from the feeder box discharge to the upper-end of the test box. After 2-3 minutes of equilibration time, four runoff samples were collected from the test box that was receiving runoff input from the feeder box. After collecting runoff samples from the test box with the feeder input, the connecting piece was removed and two additional runoff samples were collected from each box separately. These two final runoff samples were used to account for the temporal change of sediment delivery as the soil surface eroded. After all runoff samples were collected with 0% cover for the feeder box, 25% the feeder box surface was covered by pieces of plastic sheet. The sequence of collecting runoff samples was repeated: four samples from both boxes separately, four samples from test box with feeder input, and again two samples from each box separately. The same sampling procedure was repeated for 50, 75 and 100% covers of the feeder box. During each run, the volume for every sample was measured. The entire run lasted about 75 minutes.

During run progresses, shallow gully flow velocity in the test box with/without feed input was measured by using the method of coloring agent for each cover on the feeder box. The shallow gully head-cut advance with/without feed input was also measured at an interval of several minutes for each cover on the feeder box.

After each run, the samples were set overnight, the excess water was poured from bottles and the sediment was washed into 1-liter aluminum boxes. The boxes were decanted of excess water and placed in oven at 105° C for at least 12 hours or until the samples were dried. Dry weight was then taken to calculate the sediment delivery and concentration. Each run was replicated twice.

For each cover on the feeder box during the run, runoff and sediment rates were averaged from 6 samples, 4 before connection and 2 after disconnection, for both test and feeder boxes separately, and from 4 samples when two boxes are connected. These average runoff and sediment results as well as deviation range from two replication runs were presented in Table 2

The average shallow gully flow velocity with/without feed input was calculated separately, i.e., the five value of shallow gully flow velocity for five covers on feeder box with/without feed input was averaged, separately (Table 4).

**Table 2. Average runoff (R) and sediment delivery (S) data. Subscripts u, d, ud denote measurements from feeder box, test box and test box with feeder input.**

Feeder box			Test box				R <sub>ud</sub> -R <sub>u</sub> - R <sub>d</sub> L/min
Cover %	R <sub>u</sub> L/min	S <sub>u</sub> g/min	Without feeder input		With feeder input		
			R <sub>d</sub> L/min	S <sub>d</sub> g/min	R <sub>ud</sub> L/min	S <sub>ud</sub> g/min	
<b>Slope: 36.4%, rain: 50mm/h</b>							
0	1.93(0.05)*	27.2(2.2)	2.94(0.31)	146.2(7.2)	4.69(0.82)	258.6(18.6)	-0.2
25	2.67(0.06)	14.8(1.4)	2.59(0.28)	213.2(10.4)	5.20(0.58)	529.6(26.2)	-0.1
50	2.55(0.07)	7.9(1.2)	2.88(0.30)	273.2(13.6)	5.28(0.62)	696.4(36.2)	-0.1
75	2.38(0.10)	1.4(0.3)	2.74(0.18)	290.2(18.2)	5.29(0.81)	762.0(40.2)	0.2
100	2.35(0.12)	0(0)	2.78(0.21)	283.8(17.6)	5.36(0.96)	777.2(20.6)	0.2
<b>Slope: 36.4%, rain: 70mm/h</b>							
0	2.49(0.42)	55.4(6.2)	4.90(0.26)	260.6(19.8)	7.39(0.76)	518.1(18.1)	0
25	3.17(0.53)	34.6(5.8)	5.42(0.32)	499.6(30.7)	8.42(0.42)	810.3(19.8)	-0.2
50	3.21(0.72)	27.7(4.9)	5.39(0.21)	485.0(24.5)	8.41(0.85)	1381.7(23.8)	-0.2
75	3.28(0.67)	16.4(1.3)	5.32(0.19)	411.2(19.7)	8.32(0.97)	1492.4(60.2)	-0.3
100	3.30(0.75)	0(0)	5.94(0.46)	480.8(22.6)	9.26(1.02)	1920.3(50.6)	0
<b>Slope: 36.4%, rain: 90mm/h</b>							
0	4.30(0.20)	160.3(10.8)	6.24(0.36)	764.9(40.6)	9.93(0.92)	1986.8(130.2)	-0.6
25	4.34(0.18)	80.5(8.6)	6.43(0.52)	636.2(23.7)	10.64(0.96)	1684.4(100.6)	-0.1
50	4.34(0.22)	51.4 (7.2)	6.52(0.48)	454.7(18.6)	10.58(1.01)	1032.7(96.2)	-0.3
75	4.28(0.09)	19.6 (2.4)	6.62(0.72)	469.1(20.7)	10.60(0.80)	984.0(20.1)	-0.3
100	4.38(0.19)	0(0)	6.44(0.67)	468.9(22.1)	10.60(0.76)	983.2(30.2)	-0.2

\* Values in parentheses are deviation range from two replication runs.

**Table 3. Sediment concentration (C), sediment delivery (S) and up-slope effects in the test box (S<sub>ud</sub>-S<sub>u</sub>-S<sub>d</sub>). Subscripts u, d, ud denote measurements from feeder box, test box and test box with feeder input.**

Feeder box			Test box				S <sub>ud</sub> -S <sub>u</sub> - S <sub>d</sub> g/min
Cover %	C <sub>u</sub> g/cm <sup>3</sup>	S <sub>u</sub> g/min	Without feeder input		With feeder input		
			C <sub>d</sub> g/cm <sup>3</sup>	S <sub>d</sub> g/min	C <sub>ud</sub> g/cm <sup>3</sup>	S <sub>ud</sub> g/min	
<b>Slope: 36.4%, rain: 50mm/h</b>							
0	14.1(2.6)*	27.2	49.8(6.3)	146.2	55.1(8.2)	258.6	85.0
25	5.5(1.5)	14.8	82.3(8.1)	213.2	101.8(12.5)	529.6	301.6
50	3.1(0.6)	7.9	94.9(11.0)	273.2	131.9(16.2)	696.4	415.6
75	0.6(0.20)	1.4	105.9(12.8)	290.2	144.0(11.8)	762.0	466.6
100	0(0)	0	102.1(21.0)	283.8	145.0(19.6)	777.2	532.2
<b>Slope: 36.4%, rain: 70mm/h</b>							
0	22.2(4.2)	55.4	53.2(6.2)	260.6	70.1(5.6)	518.1	202.1
25	10.9(3.1)	34.6	92.2(10.4)	499.6	96.2(11.2)	810.3	276.1
50	8.6(0.7)	27.7	90.0(16.2)	485.0	164.3(16.4)	1381.7	869.0
75	5.0(0.9)	16.4	77.3(9.6)	411.2	179.4(21.2)	1492.4	1064.8
100	0(0)	0	80.9(10.2)	480.8	207.4(23.5)	1920.3	1439.5
<b>Slope: 36.4%, rain: 90mm/h</b>							
0	37.3(5.9)	160.3	122.6(13.6)	764.9	200.1(16.7)	1986.8	1061.6
25	18.5(4.6)	80.5	98.9(8.2)	636.2	158.3(9.6)	1684.4	967.7
50	11.8(2.2)	51.4	69.7(4.8)	454.7	97.6(10.2)	1032.7	526.6
75	4.6(0.9)	19.6	70.9(7.2)	469.1	92.8(9.8)	984.0	495.3
100	0(0)	0	72.8(8.7)	468.9	92.7(10.2)	983.2	514.3

\* Values in parentheses are deviation range from two replication runs.

### Sediment Data Analysis

Let S<sub>u</sub> and S<sub>d</sub> be the sediment delivery from the feeder and test boxes separately, and S<sub>ud</sub> the sediment delivery from the test box with the feeder sediment input. Depending on the magnitude of S<sub>ud</sub>, relative to S<sub>u</sub> and S<sub>d</sub>, there are some possible process scenarios on the test box (Huang et al., 1999):

- S<sub>ud</sub> = S<sub>u</sub> + S<sub>d</sub>, equilibrium, no effects from up-slope

runoff;

- S<sub>ud</sub> = S<sub>u</sub> + S<sub>d</sub>, equilibrium, no effects from up-slope runoff; or
- S<sub>ud</sub> > S<sub>u</sub> + S<sub>d</sub>, additional sediment delivery in the test box caused by the up-slope runoff.

The value B (B = S<sub>ud</sub> - S<sub>u</sub> - S<sub>d</sub>) is additional sediment delivery caused by up-slope runoff, it can indicate how the up-slope runoff can affect the detachment and transport at

down-slope shallow gully erosion area. Value  $B_s$  was tabulated in Table 3.

## RESULTS AND DISCUSSIONS

### Sediment Delivery and Sediment Regime at down-slope shallow gully area

Runoff data shown in Table 2 indicated a reasonable mass balance between total runoff from both boxes separated ( $R_u + R_d$ ) and the runoff from the test box with feeder input ( $R_{ud}$ ) under experimental conditions. On the other hand, the sediment from the test box with feeder input ( $S_{ud}$ ) was always greater than value of  $S_u + S_d$ , that is, up-slope runoff always caused additional sediment delivery in the test box (B) (Table 3). Therefore, the sediment regime was detachment-transport dominated at steep hillslope with shallow gully landscape. This result was not in agreement with previous research finding that sediment regime was deposition-transport dominated at 36.4 % slope without shallow gully landscape under 90 mm h<sup>-1</sup> rainfall intensity when sediment concentration in up-slope runoff was 50 g cm<sup>-3</sup> (Zheng et al., 2001). It is demonstrated that sediment regime and erosion process at hillslope with shallow gully landscape were different from those at hillslope without shallow gully landscape.

Table 3 and Figure 1 showed that the additional sediment delivery in the test box (B) caused by up-slope runoff was affected by sediment concentration in up-slope runoff, rainfall intensity and shallow gully erosion processes. With a decrease of sediment concentration in up-slope runoff or an increase of rainfall intensity from 50 to 70 mm h<sup>-1</sup> under a 36.4 % slope degree, the additional sediment (B) in the test box caused by up-slope runoff increased. However, the additional sediment (B) decreased with a decrease of sediment concentration in up-slope runoff at a 36.4 % slope and 90 mm h<sup>-1</sup> rainfall conditions. This reason could be attributed to shallow gully developing processes.

Under conditions of 50 and 70 mm h<sup>-1</sup> rainfall intensities at a 36.4% slope, shallow gully deep cutting and head-cuts advance gradually developed with run progresses. Figure 2 showed that during the run progress, sediment delivery with or without feeder input was associated with shallow gully head-cut advance. Under 70 mm h<sup>-1</sup> rainfall intensity, a shallow gully head-cut occurred at 9-min of the run, and then the head-cut advanced with the run progress. When shallow gully head-cut advanced rapidly, sediment delivery increased; when the shallow gully head-cut advanced slowly, sediment delivery obviously decreased. Meanwhile, up-slope runoff discharging into the test box enhanced shallow gully head-cut, which caused a great increase of sediment delivery in the test box. Figure 3 demonstrated that under conditions of 90 mm h<sup>-1</sup> rainfall at a 36.4 % slope, shallow gully head-cut occurred at 6-min after run, and ceased at 17-min because the head-cut developed quickly and stretched to the top of the test box at 17-min. At the beginning at 6-min and ending at 17-min of the run, sediment delivery was associated with the shallow gully head-cut advance. After 17-min of the run, shallow gully head-cut ceased, sediment delivery in the test box greatly decreased. The average sediment delivery with and without

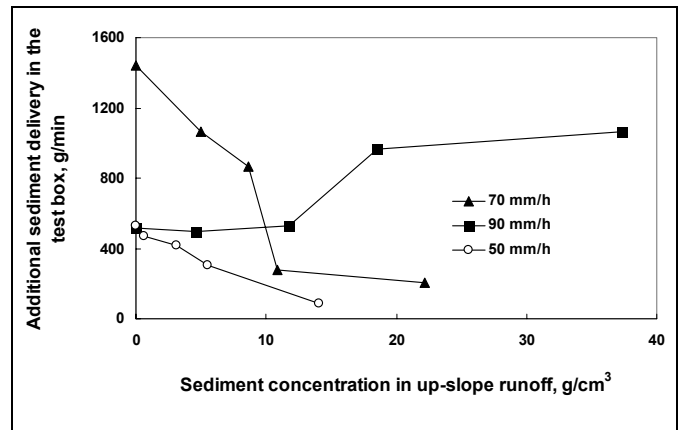


Figure 1. The relation between additional sediment delivery in the test box caused by up-slope and sediment concentration in up-slope runoff.

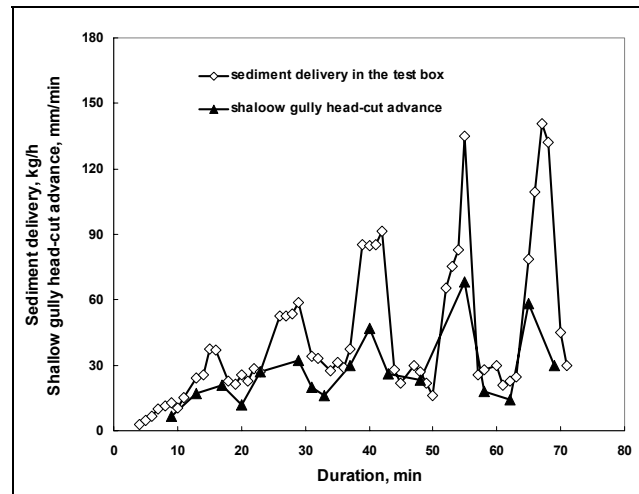


Figure 2. Sediment delivery and shallow gully head-cut advance in the test box (70 mm/h rainfall).

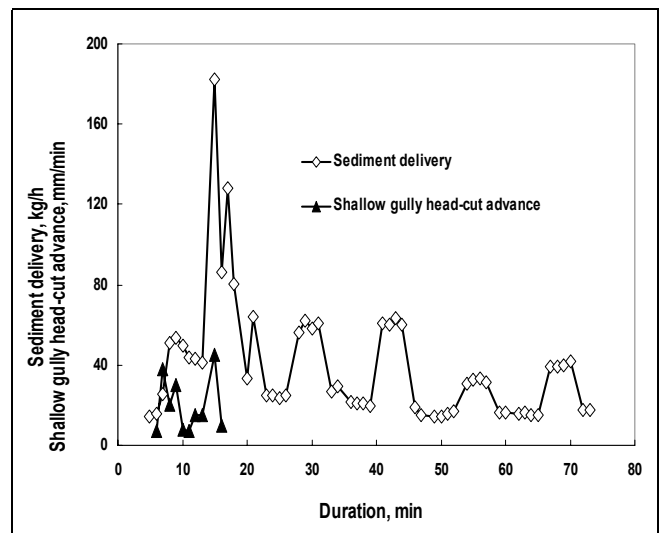


Figure 3. Sediment delivery and shallow gully head-cut advance in the test box (90 mm/h rainfall).

**Table 4. Shallow gully flow velocity (V) with/without feeder input in the test box.**

Slope %	Rain Intensity mm h <sup>-1</sup>	Shallow gully velocity, cm/min		
		Without feeder input V <sub>d</sub>	With feeder input	
			V <sub>ud</sub>	V <sub>ud</sub> /V <sub>d</sub>
36.4	50	21.7(1.3)*	31.6(0.8)	1.46
36.4	70	23.1(2.6)	36.6(1.7)	1.58
36.4	90	25.6(3.8)	37.8(2.6)	1.48

\*Values in parentheses are deviation range from all measurements.

feeder input changed from 120 to 50 kg h<sup>-1</sup>, and from 50 to 20 kg h<sup>-1</sup>, separately. These results showed that shallow gully erosion process played an important role in erosion processes with shallow gully landscape.

### Shallow Gully Erosion Importance

The erosion at the down-slope shallow gully erosion area includes shallow gully channel erosion, i.e., shallow gully head-cut, deep cutting, and sidewall collapse, and rill erosion and sheet erosion between shallow gullies. It was measured that under 50, 70 and 90 mm h<sup>-1</sup> rainfall intensities, erosion amount in shallow gully channel occupies 91.0, 77.6, and 56.6% of total erosion amount, respectively. Those results are the same as we got from field study (Zheng et al 1997). Those also indicated that shallow gully erosion plays an important role at steep hillslopes of the Loess Plateau. Therefore, soil erosion model in the Loess Plateau should include shallow gully erosion.

### Effects of Up-slope runoff on Shallow Gully Flow Velocity

When up-slope runoff discharged into shallow gully channel at the down-slope section, shallow gully flow velocity increased by 45 to 58% (Table 4). The increase of shallow gully flow velocity enhanced shallow gully deep cutting, head-cut advance, and sidewall collapse. Therefore, sediment delivery at the down-slope shallow gully section greatly increased. This result demonstrated that up-slope discharging into down-slope shallow gully section greatly increased shallow gully flow velocity, which enhanced shallow gully erosion process, and increased sediment delivery.

### CONCLUSIONS

A dual-box system, consisting of a 2-m sediment feeder box and a 3-m test box, was used to quantify how up-slope runoff affects erosion processes at the shallow gully erosion area. During this study, different levels of sediment concentration from the feeder box were controlled by covering portions of the feeder box surface. The up-slope runoff effects were studied under 50, 70 and 90 mm h<sup>-1</sup> rainfall with a 36.4% slope.

Under experimental conditions, sediment regimes were always detachment-transport dominated at steep slope with shallow gully landscape. The additional sediment detachment at a down-slope shallow gully area caused by the up-slope runoff increased with a decrease of sediment concentration in up-slope runoff or an increase of rainfall intensity, and the sediment delivery during the run was associated with active shallow gully head-cut advance.

When shallow gully head-cut advance ceased, sediment delivery in the test box with/without feed input kept constant value. An increase of shallow gully flow velocity after up-slope runoff discharging into down-slope section was a key reason of sediment delivery increase in the down-slope section. In a rainfall event, the sediment delivery at the down-slope was dominated by erosion amount of shallow gully channel where single shallow gully rapidly developed.

Our results showed that sediment delivery at a slope section depends not only on rainfall, runoff intensity, slope gradient, and surface conditions, but also on the sediment concentration from the up-slope area and erosion processes. Therefore, understanding on interaction of runoff and sediment at up-slope and down-slope and erosion process during rainfall is important for erosion modeling at the Loess Plateau.

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