Soil Erosion, Deposition and Transport Processes at Hillslopes of the Loess Plateau

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Abstract: Soil detachment, deposition and transport processes occur simultaneously during erosive rainfall events. Up to date, numerous studies have been conducted on soil detachment, deposition and transport processes. However, how to quantitatively depict detachment, deposition and transport is a still unsolved problem. Studies on detachment, deposition and transport processes are important for establishing a process-based erosion model. A dual-box system (one is a feeder box located at up-slope, and the other is a test box located at down-slope) was used to quantify hillslope detachment-deposition-transport processes and run-on water and sediment effects on down-slope erosion process. The results showed that sediment regime was detachment-transport dominant when rill erosion or shallow gully erosion was dominated at steep hillslopes. Up-slope runoff discharging into down-slope caused the additional sediment delivery (net detachment) at down-slope section. The net detachment caused by up-slope runoff increased either a decrease of sediment concentration in up-slope runoff and an increase of rainfall intensity, or change of surface conditions from dry to wet. Rill erosion, ephemeral gully erosion played important roles in hillslope erosion process. Sediment delivery at steep hillslope was associated with rill head-cuts advance or ephemeral gully head-cuts advance. These findings will help to improve the understanding of run-on water and sediment effects on down-slope erosion process and control strategies to minimize the run-on water impacts.

Keywords: erosion process, sediment regime, run-on water and sediment effects, rill erosion, shallow gully erosion, the Loess Plateau

1 Introduction

During erosive rainfall process, up-slope runoff with variable sediment moving down-slope affects erosion processes, i.e., detachment, deposition and transport, at down-slope segment, especially at loessial hillslopes on the Loess Plateau of China, where soil erosion have obvious vertical zonation, i.e., sheet erosion, rill erosion and shallow gully (like ephemeral gully) erosion zones from boundary to gully edges. However, there is limited data to show how up-slope runoff with variable sediment affects detachment, deposition and transport processes at down-slope section.

An early conceptual model of the effects of sediment concentration in the eroding water on erosion processes was proposed more than 50 years ago by Ellison (1947) and Ellison and Ellison (1947). This model considers that clear water has a maximum transporting capacity, minimum detaching capacity and causes very little erosion. On the other hand, when the water is full of sediment, it has a maximum detaching capacity, minimum transporting capacity and again very little erosion. Maximum erosion occurs when the flow contains just enough abrasive sediment to detach as much soil as the flow will carry.

Despite Ellison’s original hypothesis on how sediments in the runoff water would affect erosion processes, little work has been done to test the validity of these concepts. Nevertheless, field studies conducted on the steep hillslopes in China demonstrated that significance of up-slope runoff with variable sediment effects on down-slope sediment production (Chen, 1992, 1993; Zheng *et al*., 1998, 2000). Since conditions in the steep hillslopes of the Loess Plateau are very complex, it is difficult to identify quantitatively how up-slope runoff and sediment affects the down-slope erosion process under different rainfall, runoff, slope steepness and surface condition.

Recently, the normal single 5 m soil box was expanded to a dual-box system to further study erosion process and sediment regime for a hillslope segment. Huang *et al.* (1999) designed a dual-boxes system of 1.8 m sediment source (or feeder) box and 5 m test box to quantify effects of different runoff rates with different sediment concentration on down-slope erosion processes. They reported increases of slope, rainfall intensity, and soil erodibility caused that dominant erosion process shifted from detachment-limiting to transport-limiting. Later on, Zheng *et al.* (2000) used the above dual-boxes system to study run-on water and sediment effects on down-slope erosion process under different slopes, rainfall intensities, and near-surface soil moisture gradients. Their research results showed that erosion processes and sediment regimes were changed by sediment concentration in up-slope runoff, rainfall intensity, and surface conditions.

Motivated by previous field observations in China and the capability of a dual-box system to simulate hillslope erosion processes, the objective of this study was to quantify up-slope runoff and sediment effects on erosion processes at down-slope rill erosion dominated zone, and shallow gully dominated zone. Results of this study will further the understanding of soil erosion processes and provide a data for the development of a more accurate process-based erosion model.

2 Materials And Methods

Experimental Setup

The clayey loess collected from Yangling town, Shanxi Province of China, was used in this study. The soil was sampled from a very deep soil layer (6 m deep) of cropland, which layer would be C-Horizon. This soil had about 8.3% sand, 67.4% silt, and 24.3% clay. The study was conducted on a dual-box system consisting of a 3m long test box and a 2m long feeder box with 36.4 % slope. Both boxes were 1.5m 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 of soil boxes, the soil depth was approximately 60 cm. These two boxes were placed under two simulators with side-nozzle. The height of raindrops falling was 16 m. Experimental design included two independent laboratory studies. The first study was designed to quantify effects of up-slope runoff and sediment on erosion process at downslope rill erosion dominated zone. The experimental variables in this study included two rainfall intensities: 70 and 90 mm/h, three surface conditions: dry, wet and crust. Soil moisture contents were 19.2% for dry surface treatment and 27.5% for wet and crust surface treatment. For the dry surface treatment, a 10 min pre-rain of 30 mm h-1 was applied prior 2 h to erosion run and no any runoff occurred at soil boxes. For the wet surface treatment, the pre-run rainfall lasted 20 min. For the crust surface treatments, a 12 min rainfall of 50 mm h-1 was applied prior 24 h to the run. The second study was designed to quantitatively identify effects of up-slope runoff with variable sediment on erosion and transport processes at down-slope shallow gully erosion dominated zone under 50 and 70 mm/h of rainfall intensities. Soil moisture contents were 25 % to 26%. A 20 min pre-rainfall of 30 mm h-1 was applied prior 24 h to erosion run.

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 and sediment effects on shallow gully erosion process, an initial shallow gully shape was made in the test box according to measurement data from contour map. These two soil boxes were packed in 5 cm layers to ensure uniform density. Soil bulk density was 1.12 $g \cdot cm^{-3}$ to 1.15 $g \cdot cm^{-3}$.

Experimental Procedures

The sediment concentration in the feeder box was varied by progressively covering portions of the surface with plastic sheet to create same runoff volume with different sediment concentration during each run. The run started with 0 cover on the feeder box, thus the highest level of sediment and ended with

100% cover on the feeder box. Runoff samples from both feeder and test boxes were collected, in one-minute interval, separately, and from the test box with feeder input during the run following the sampling procedure of Zheng *et al*. (2000). During the run, rill and shallow gully flow velocity in the test box with/without feeder input was measured by dye tracing. The rate of head-cuts advance of rills and shallow gullies with/without feeder input was also measured. The entire run lasted about 75 minutes. Each run was replications twice.

Sediment Data Analysis

The sediment mass balance scenario proposed by Huang *et al*. (1999) was used to analyze the up-slope sediment effects on erosion process at a down-slope segment. Let S_u and S_d the sediment delivery from the feeder box and test box separately, and S_{ud} the sediment delivery from the test box with the feeder sediment input. Depending on the magnitude of S_{ud}, relative to S_u and S_d, there were some possible process scenarios in the test box:

$S_u < S_{ud} < S_u + S_d$, simultaneous erosion and deposition, erosion> deposition;

$S_{ud} = S_u + S_d$, equilibrium, no effects from feeder water and sediment;

$S_{ud} > S_u + S_d$, additional sediment delivery in the test box caused by the feeder water.

We define B as $S_{ud} - (S_u + S_d)$, to represent the additional sediment delivery (net detachment) caused by up-slope runoff. Therefore, the value of B quantifies how up-slope runoff and sediment affect the erosion process at the down-slope rill erosion dominant zone and shallow gully dominant zone.

3 Results And Discussions

3.1 Sediment Detachment and Regime at down-slope rill erosion dominated zone and shallow gully erosion dominated zone

Runoff data shown in Table 1 and Table 2 indicated a reasonable mass balance between total runoff from the feeder box and test box 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 delivery from the test box with feeder input (S_{ud}) was always greater than value of $S_u + S_d$. The results indicated that up-slope runoff always caused the additional sediment delivery (net detachment) in the test box (*B*), and sediment regime was detachment-transport dominated in rill erosion dominant zone and shallow gully erosion dominated zone on steep hillslopes.

Table 1 Average runoff (*R*), sediment concentration (*C*), and sediment delivery (*S*) data from the first study. Subscripts *u, d, ud* denote measurements from feeder box, test box without feeder input, and test box with feeder input

Feeder box				Test box						B*
				Without feeder input			With feeder input			
Cover %	R_u L/min	C_u kg/m^3	S_u G/min	R_d L/min	C_d kg/m^3	S_d g/min	R_{ud} L/min	C_{ud} kg/m^3	S_{ud} g/min	g/min
70mm/h rainfall, dry surface										
0	3.1	15.5	48.0	4.1	27.4	112.5	7.2	28.2	203.3	42.8
25	3.4	11.7	39.8	4.3	28.9	124.3	7.5	36.9	277.1	113.0
50	3.4	8.2	27.8	4.3	33.0	141.9	7.6	39.0	296.5	126.8
75	3.5	4.7	16.6	4.4	33.3	146.5	7.7	49.7	382.7	219.6
100	3.6	0.0	0	4.4	31.9	140.2	7.8	49.7	387.5	247.3
70mm/h rainfall, wet surface										
0	3.3	10.1	33.3	4.6	36.3	166.8	7.9	48.5	383.3	183.2
25	3.3	6.5	21.6	4.7	37.1	174.2	8.0	50.9	407.0	211.2
50	3.3	5.9	19.4	4.7	35.0	164.7	8.0	49.9	399.2	215.1
75	3.3	3.8	12.4	4.7	34.9	164.2	8.0	50.1	400.8	224.2
100	3.4	0.0	0.0	4.7	34.9	164.2	8.0	49.6	397.1	232.9

Continued Table 1

70mm/h rainfall, crust surface										
0	3.1	13.7	42.5	4.4	27.2	119.6	7.5	27.7	207.6	45.5
25	3.0	9.7	29.2	4.6	32.4	149.2	7.6	33.4	253.7	75.3
50	3.4	6.6	22.5	4.7	24.8	116.6	7.9	26.8	211.9	72.8
75	3.4	3.1	10.4	4.6	21.7	100.0	7.7	23.8	183.3	72.9
100	3.3	0.0	0.0	4.6	21.5	98.9	7.6	23.1	175.2	76.3
90mm/h rainfall, dry surface										
0	4.0	16.2	64.8	5.8	39.8	230.9	9.6	50.5	485.0	189.3
25	4.2	8.9	37.3	5.5	34.8	191.6	9.6	45.6	437.7	208.8
50	4.5	6.0	27.0	5.5	35.2	193.6	9.7	47.1	457.3	236.7
75	4.7	2.2	10.5	5.6	34.8	195.0	10.0	62.3	622.5	417.0
100	4.6	0.0	0.0	5.6	33.9	189.7	10.0	66.5	665.1	475.4
90mm/h rainfall, wet surface (I)										
0	4.3	39.3	169.1	5.5	75.2	413.7	9.8	70.2	687.5	104.7
25	4.2	26.0	109.3	5.9	44.7	263.9	9.8	54.5	534.5	161.3
50	4.4	17.6	77.3	5.7	44.9	255.8	9.8	51.6	505.7	172.6
75	4.4	9.3	41.0	5.6	46.4	259.7	9.8	48.4	474.6	173.9
100	4.3	0.0	0.0	5.7	45.6	259.8	9.8	48.7	476.8	217.0
90mm/h rainfall, wet surface (II)										
0	4.3	48.4	208.1	6.1	79.8	487.0	10.2	64.0	683.9	–11.2
25	4.0	24.3	104.7	6.2	50.2	311.1	10.0	65.9	658.9	243.1
50	4.4	14.0	61.5	6.2	53.3	330.4	10.4	67.1	698.0	306.1
75	4.4	8.6	37.7	6.1	90.3	550.7	10.4	142.7	1484.4	896.0
100	4.4	0.0	0.0	6.0	132.8	797.0	10.3	171.8	1769.3	972.3

$B = S_{ud} - S_u - S_d$

Table 2 Sediment concentration (*C*), sediment delivery (*S*) and up-slope effects in the test box (S_{ud}-S_u-S_d) from the second study. Subscripts u, d, ud denote measurements from feeder box, test box and test box with feeder input

	Feeder box		Test box				S_{ud}-S_u-S_D (B^*)
			Without feeder input		With feeder input		
Cover %	C_u G/cm^3	S_u G/min	C_d g/cm^3	S_d g/min	C_{ud} g/cm^3	S_{ud} g/min	g/min
Slope: 36.4%, rain: 50mm/h							
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
Slope: 36.4%, rain: 70mm/h							
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

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

The data from Table 1 and Table 2 showed that the net detachment (*B*) was affected by sediment concentration in up-slope runoff, rainfall intensity and surface conditions. Either a decrease in up-slope sediment concentration or an increase of rainfall intensity resulted in *B* increase. Meanwhile, when change of soil surface conditions from dry to wet for 70 mm h^{-1} of rainfall, *B* also increased. These data also demonstrated the interaction of surface conditions and rainfall intensity on sediment delivery and net detachment (*B*). Therefore, it is important to understand and focus on the interaction of surface conditions and rainfall on erosion process.

3.2 Effects of Rill Head-Cut and Shallow Gully Head-cut Advances on Sediment Delivery

The advances of the rill head-cuts and shallow gully head-cuts were recorded and presented together with the sediment delivery, separately (Figure 1 and Figure 2). The sediment delivery peaks in Figure 1 and Figure 2 were from the period when the test box was receiving up-slope sediment input. Figure 1 and Figure 2 showed that sediment deliveries were closely associated with the advance of rill head-cuts or shallow gully head-cuts in the test box. This shows that up-slope runoff discharging into a down-slope segment greatly enhanced rill head-cuts advance or shallow gully head-cuts advance, and sediment delivery. These results showed that rill erosion and shallow gully erosion have important effects on erosion process at steep slope landscape.

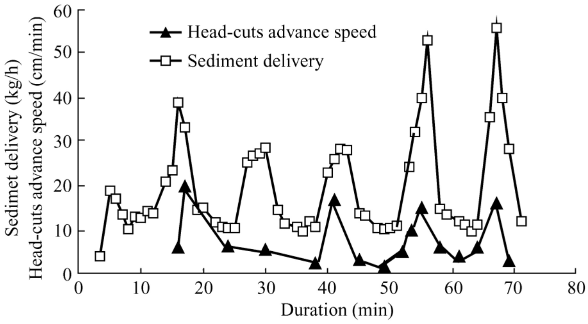

Fig. 1 Sediment delivery changes with rill head-cut development

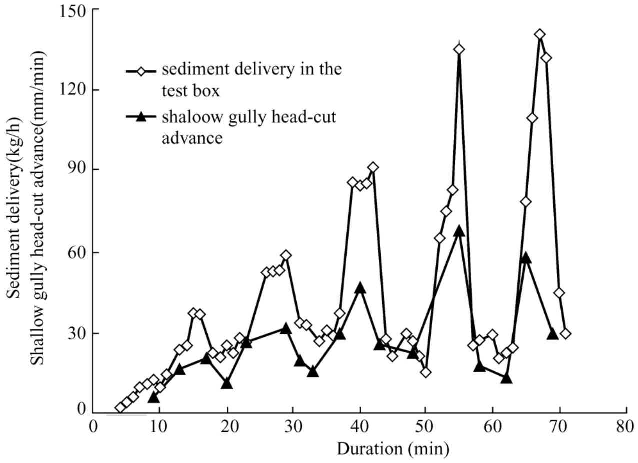

Fig. 2 Sediment delivery changes with shallow gully head-cut development under 70 mm/h of rainfall intensity

3.3 Shallow Gully Erosion Importance

The erosion at the down-slope shallow gully erosion dominant zone includes shallow gully channel erosion, i.e., shallow gully head-cuts, deep cutting and wall collapse, and rill erosion and sheet erosion between shallow gullies. It was measured that under 50 mm • h^{-1} and 70 mm • h^{-1} rainfall intensities, erosion amount in shallow gully channel occupies 91.0%, 77.6%, and 56.6% of total erosion amount, respectively. Those results were the same as we got from field study (Zheng *et al.*, 1998). 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.

4 Conclusions

A dual-box system, consisting of a 2m sediment feeder box and a 3m test box, was used to quantify how up-slope runoff affects erosion processes at the down-slope rill erosion dominant zone and shallow gully erosion dominant zone. During this study, different levels of sediment concentration from the feeder box were controlled by covering portions of the feeder box surface.

Under experimental conditions, sediment regimes were always detachment-transport dominated at down-slope rill erosion dominated zone and shallow gully erosion dominated zone on steep hillslopes. The additional sediment delivery at a down-slope section caused by the up-slope runoff was affected by sediment concentration in up-slope runoff, rainfall intensity and surface conditions. The sediment delivery during the run was associated with active rill and shallow gully head-cuts advance. The rill and shallow gully erosion had great contribution to erosion process and sediment regime on steep hillslopes of the Loess Plateau.

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 section 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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