Soil Moisture Distribution and Runoff Generation in a Gully System

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Abstract: Gullies are severe stages of water erosion and gully erosion is a very serious problem on the loess plateau of China. So far very few soil erosion models can predict gully erosion. To develop and validate a gully erosion model, it is necessary to understand the relationship between soil moisture and runoff generation that affects the gully erosion. An automatic raingauge, 29 TDR (Time Domain Refectometry) sensors, an H-flume together with an ultrasonic water level sensor and a turbidity sensor, and a computer system were installed in a small gully watershed on loess plateau of China. Rainfall, soil moisture, runoff and sediment were continually monitored and recorded in a 12-hour interval generally and 20-minute interval during rain events through 1998—2000. Soil moisture spatial distributions and temporal changes were different in the gully and in different depths. Crop fields in the upland had the highest soil moisture, then was gully floor, and the gully side slopes in order, the vertical gully side wall had the lowest values. Average soil moisture was 10.0%—11.7% at 15cm depth and 10.2%—13.1% at 30cm depth of the upland, around 7.1%—7.7% of the gully floor, 7.1%—7.5% of the gully side slope, and 4.5%—6.0% of the vertical cliff. Soil water content also varied with depth. The shallow layers were more active than deep layers, and thus /moisture in these layers was higher in a wet period or wet year and lower in a dry period or dry year than that of deep layers. Generally, runoff occurred when the maximum 5-minute rainfall intensity exceeded 30mm/hr. The duration of runoff was very short in this area, and was 10—20 minutes normally.

Keywords: gully erosion, rainfall, soil moisture, runoff

1 Introduction

Gullies are severe stages of water erosion (Brooks *et al.*, 1997). Gully erosion is a very serious problem on the loess plateau of China. It breaks land apart into small pieces, reduces the productive area and agricultural productivity, and causes many environmental problems. For example, large amount of sediments were moved from the upland areas to the downstream of the Yellow River, and made the river bed higher and higher which menaces the safety of people's life and the sustainable development of society.

So far very few models can predict gully erosion. LISEM-the Limburg Soil Erosion Model (De Roo *et al.*, 1996), was chosen to be used in soil conservation planning in the Erochina project, but LISEM does not include the component of gully erosion. It was therefore necessary to develop a component for gully erosion prediction.

Overland flow is important on the gully initiation and development (Bull and Kirkby, 1997; Bocco, 1991). In general, two types of overland flow can be distinguished, namely Hortonian overland flow which occurs when the rainfall intensity exceeds the infiltration capacity (Horton, 1933), and saturation overland flow which occurs when the soil profile is saturated with water thus preventing any further infiltration (Dunne, 1978). Overland flow resulting from rainfall intensity exceeding the soil infiltration capacity are thought to be an important runoff generating mechanism in semi-arid areas with high rainfall intensity events (Fitzjohn, 1998). In this situation initial soil moisture may not be important. However, in many situations runoff is generated due to the saturation of near surface horizons (Fitzjohn, 1998). In the southern part of The Netherlands, for example, surface runoff was initiated after saturation of the top 5cm—10cm of the soil horizon (Ritsema *et al.*, 1996). Soil moisture is a key factor in determining the surface runoff response to a given rainfall event.

To develop a gully erosion module within the LISEM model, a gully watershed in Danangou catchment was selected to measure the gully erosion and the correspondence between rainfall, soil moisture and runoff. This data was used for calibration and validation of the model. By measuring the soil moisture in different depths and gully positions, the distribution of soil moisture on the gully upland, gully sides, and the gully floor were analyzed. This measurement also showed how the runoff was generated corresponding to the rainfall. The objective of this study was to know: (1) the spatial and temporal changes of soil moisture in a gully system and the related influencing factors; (2) the relationship between the runoff generation and rainfall in a small gully system.

2 Materials and methods

A gully and its corresponding runoff catchment area, a so-called gully watershed was selected to measure its hydrology and sediment features. It is located in Danangou catchment, Ansai County of Shaanxi Province in China. It is a typical loess plateau region and has a monsoon climate. The average annual rainfall from 1961 to 1990 is 561mm, and the main rain season is in summer. More than 90% of annual rainfall falls from April to October. The area of the gully watershed is about 2,000m^2. It could be geomorphologicaly divided into three parts: upland area with relatively gentle slope 0°-30°, from which drainage runoff water flowed into the gully; side slope areas with multifarious of slope, 35°-90° generally; and the gully floor with a typical 30° slope. The elevation of the gully floor is around 1,125m, and about 1,145m to the upland.

The measurement consisted of rainfall amount by a automatic tipping bucket raingauge, Environment Measured Ltd ARG100; soil moistures by 29 TRIME TDR (Time Domain Refectometry) sensors; water level by an ultrasonic sensor and sediment concentration by a turbidity sensor installed in a H-flume installed at the gully outlet. The whole measuring system was controlled by a HP200LX palmtop computer as the data logger system. The computer checked the rain gauge every 5 minutes. The TDR system was triggered to do ‘fast’ measurement, once every 20 minutes, when the rainfall exceeded 0.6mm in 5 minutes. This was done as long as it was raining. When the rain stopped, the TDR system would continue to do ‘fast’ measurements for a period of 5 hours. After these 5 hours, it would fall back into its ‘slow’ measurement frequency, once every 12 hours. The level sensor in the H-flume did a measurement every 5 minutes and the turbidity sensor did a measurement every 12 hours as the ‘slow’ measurement. When a level of more than 1cm of water is detected (1.5% level of a total 61cm), the level and turbidity would be measured every 30 seconds as the ‘fast’ measurement frequency. This was done as long as there was a level of more than 1.5%(1cm). If the level dropped below this value, the ‘fast’ measurements were changed into ‘slow’ status. The TDR sensors measured the percentage of volume water content in soil profiles. The water levels recorded in the flume could be transferred to the runoff discharge based on the relationship between water level and discharge of the H-flume.

To measure the soil moisture changes in the gully watershed, the TDR sensors were 29 installed in different gully positions (Table 1). It was classified into 3 groups. The first group comprising 6 TDR sensors was located on the upland area, that is used as cropland. It had 3 sites with 10°, 15° and 30° slopes respectively and 2 depths (15cm and 30cm) of each. The second group was set on the gully sides including 19 TDR sensors of which 16 were installed in the gully side slopes of 35°, 40°, 50° and 80° respectively, and 3 were installed in an erosion ‘pipe’. The third group consisted of 4 TDR sensors, which were installed in the gully floor having 30° slope. 2 were installed in the upper part at 40cm and 100cm depth, and the other 2 were installed in the lower part at the same depth horizontally as the upper sensors.

Table 1 The Distribution of TDR sensors in the gully watershed

Gully position	Position on slop	Sensor Code	Slop (°)	Depth (cm)	Distance[†] (cm)	Distance[‡] (cm)	Land use
Upland	Upper	A1	10	15			Cropland
		A2	10	30			
	Lower	C4	15	15			
		C5	15	30			
Gully Side Slope Surface	Upper	F1	35	28	90	40	Waste Grassland
		F2	35	52	90	100	
		B5	80	100	102	50	
	Middle	E2	50	48	190	40	
		F3	35	28	290	40	
		E4	50	48	340	40	
	Lower	E6	50	48	470	40	
Gully Side Slope Deep		E1	50	119	190	100	
		B6	80	125	127	50	
		F4	35	140	290	200	
		E5	50	262	470	220	
Gully Side Pipe		C1	90	50	50	40	
		C2	90	100	100	40	
		C3	90	150	150	40	
Gully Floor	Upper	D1	30	40			Waste Grassland
		D2	30	100			
	Lower	D3	30	30			
		D4	30	100			

[†] Distance from the upper edge of the gully slope; [‡] Distance from the slope surface to the TDR sensor

3 Results

3.1 Precipitation during three measuring seasons

Precipitation is the only water supply for the soil moisture in the study area, and thus soil moisture changes depend mainly on rainfall. During the measuring years of 1998—2000, precipitation in measuring season (from April to October) was very different. The measured rainfall during April to October was 568mm in 1998, 223mm in 1999 and 250mm in 2000. Compared to the average rainfall of this period, 517mm, from 1961 to 1990 in this region, 1998 was a wet year, but both 1999 and 2000 were dry years, which only 43.1% and 48.4% of the average value fell.

3.2 Soil moisture on the upland

The soil moisture condition of the upland crop field was very sensitive to rainfall. Both layers at 15cm and 30cm depths changed greatly in accordance to the rainfall. The variation of soil water content in the surface layer (15cm) was greater than that in the deeper layer (30cm). Generally speaking, during a rain storm or a wet year, soil moisture of shallow layer was higher than that of deep layer. The average soil water content was 12.1% at 15cm depth and 11.5% at 30cm depth in 1998. Inversely, during a dry period or a dry year, water content of shallow layers was lower than that of deeper layers, which were 7.8% at 15cm and 8.9% at 30cm depths in 2000. In the dry year (1999), the shallow layer had a low moisture condition most of the time (Fig.1). In the extremely dry year of 2000, the shallow layer water content was lower than the deeper layer during the whole year. Soil moisture continuously decreased from 1998 to 2000. Although the rainfall in 2000 was a little more than in 1999, soil moisture was lower in 2000 than in 1999. This shows that the previous year rainfall condition influences the second year's water content.

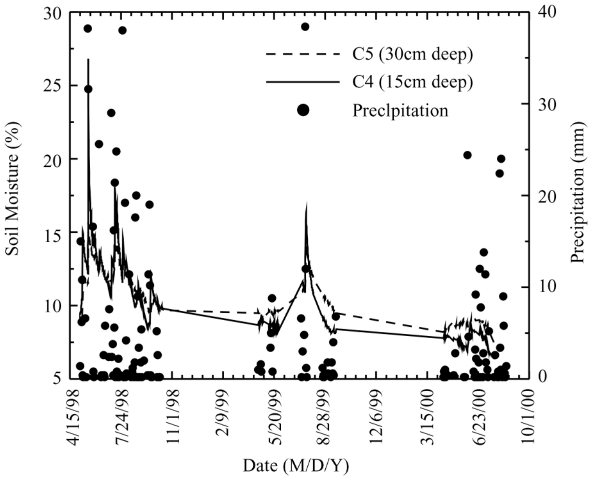

Fig. 1 Soil moisture of crop field on the upland

3.3 Soil moisture on the gully sides

Soil moisture less than 119cm deep in the gully side slopes changed greatly corresponding to rainfall. The depth in which moisture varied was down to 119cm deep in the wet year (Table 2) and only down to 48cm deep in the dry year. So the layers above 120cm are regarded as the surface layer where the variation of soil water content is determined greatly by the balance of rainfall and evaporation. For the surface layer, soil water content changed with the different slope positions. The upper side slope showed the lowest moisture values, because it had two evaporating surfaces both on the upland and slope. Sensors F1, F2 and B5, located in the top slope, showed the lowest moisture values, 5.0%—6.2% through 1998 to 2000 (Table 2). Inversely, the lower part of the side slope showed the highest moisture values, 8.1%—13.0% from 1998 to 2000, because the moisture in this part was supplied by water coming from the gully floor. In the middle slope segment, water content was 5.3%—7.6%, between the values of top and lower parts. The soil moisture of layers deeper than 120cm varied according to depth. The deeper the layers, the higher and the more stable the soil moisture (Table 2). The layer of 262cm deep had much higher water content than other layers and was more stable. Moisture in the shallow layers (28cm and 48cm deep) varied in both wet and dry years. At a depth of 119cm, it varied only during the wet year. This shows that the rainfall could supply soil water down to the 119cm deep in a wet year, but only to a depth of 48cm in a dry year.

Basically, moisture on the gully 'pipe' was low and stable. Average water content was 4.5% at 50cm, 5.5% at 100cm, and 6% at 150cm distance from the top edge, close to the wilting point. These low values are related to the high evaporation rate here. Through 1998—2000, there was not any significant change for the cliff moisture.

Table 2 Soil moisture of different layers on the gully side slopes

		Top				Middle				Low	
Sensor Code		F2	F1	B5	E2	E1	F3	F4	E4	E6	E5
Distance(cm)[†]		90	90	102	190	190	290	290	340	470	470
Depth (cm)		28	52	100	48	119	28	140	48	48	262
Moisture (%)	1998	6.2	6.2	5.9	7.6	8.6	7.2	7.2	7.6	13.0	12.0
	1999	5.3	5.3	5.5	5.9	6.9	6.2	7.9	5.9	10.0	12.1
	2000	5.1	5.0	5.3	5.3	6.5	6.3	7.3	5.6	8.1	11.6
	Average	5.5	5.5	5.6	6.3	7.4	6.6	7.5	6.4	10.3	11.9

[†] Distance from the upper edge of the gully slope

3.4 Soil moisture on the gully floor

Changes of soil moisture at different depths on the gully floor were similar to those in the crop fields of the upland. Surface moisture values were higher than those of deep layers in the wet year or during rainfall events and had an opposite trend in the dry year or in dry periods. Compared to the cropland, the gully floor showed lower water contents. The surface soil moisture (30cm—40cm deep) in the gully floor was 8.9%—12.0% in 1998, 5.7%—6.5% in 1999, and 5.4%—5.9% in 2000. For the cropland of the upland at 30cm depth, it was 11.5%—14.9%, 10.7%—12.6%, and 8.9% respectively.

From the above analysis, can be concluded that soil moisture and time were different at different gully positions. Comparing soil moistures at different gully positions, crop fields in the upland had the highest soil moisture, 10.0%—11.7% at 15cm depth and 10.2%—13.1% at 30cm depth. Moisture in the gully floor was the second highest, around 7.1%—7.7%, and gully slopes were dryest with moisture values of 7.1%—7.5%. The gully erosion ‘pipe’ was extremely dry. Soil water content variation was also different at different depths. The shallow layers were more active than deep layers, and thus the moisture of the surface layers was higher in a wet year and lower in a dry year than that of deeper layers. Rainfall was transported down to 100cm—120cm depth in a wet year, and only to 40cm—50cm depth in a dry year.

3.5 Runoff generated in the gully watershed

Not all rain storms generate runoff causing soil erosion. To make the calculation of rainfall erosivity more accurate and less elaborate, USLE (Universal Soil Loss Equation, Wischmeier and Smith, 1978) and RUSLE (Revised Universal Soil Loss Equation, Renard *et al*., 1997) only calculated the rainfall erosivity when the total amount of rainfall was higher than 12.7mm. Many studies showed that runoff might be generated when total rainfall was higher than 10mm on the loess plateau of China (Wang, 1984; Jiang and Li, 1988). But here it is more sensitive to the rainfall intensity, especially to the maximum rainfall intensity for a certain period such as 5, 10, or 30 minutes (Wang, 1984). The rainfall of maximum 5-minute intensity exceeding 25.9mm/hr—28.8mm/hr would results in the runoff on loess plateau of China (Liu, 1990; Xie, *et al*., 2000). Through the measuring years 1998—2000, there were 23 rainfall events that exceeded 10mm, and only 9 runoff events occurred. They occurred 7 times in 1998, a wet year, and 1 time each in 1999 and 2000, dry years. Of 9 runoff events, 5 had maximum 5-minute rainfall intensity exceeded 30mm/hr, the same as Liu and Xie found. 2 had higher rainfall intensity, 38.4mm/hr and 43.2mm/hr each, but the rainfall duration was too short to cause the runoff. The rainfall in 10 minutes was only 6.3mm and 6.4mm. 2 had low rainfall intensity, 19.2mm/h of each.

The runoff procedures of the gully watershed in the study area responded fast responding to high intensity rainfall events. The reaction time from runoff start to the peak rate was only 3—7 minutes, but the decline took longer, 5—16 minutes. This was similar to the runoff measurements in the Tuanshangou plot of loess plateau, with almost the same area as our study gully watershed (unpublished data). From 1998 to 2000, the maximum peak rate was 0.063m^3/s on July 20 of 1999, and the minimum peak rate was 0.002 m^3/s on July 5 of 1998 (Table 3). The longest duration of runoff was about 20 minutes and the shortest was 10 minutes.

Table 3 Runoff characteristics

date	Rainfall	Duration	Maximum of 5-minute intensity	Peak rate	Duration for peak rate	Decline duration
	mm	min	mm/hr	m^3/s	min	min
Jul-5-98	28.8	835	50.4	0.002	5	5
Jul-12-98	21	1,030	45.6	0.023	4	16
Jul-15-98	24.2	150	67.2	0.015	5	7
Aug-1-98	19	455	96	0.024	3	7
Aug-23-98	19.8	275	33.8	0.007	7	9
Jul-20-99	38.2	355	112.8	0.063	5	15
Aug-29-00	7.8	15	48	0.008	5	9

4 Conclusions

Based on the measurement of soil moisture in a gully watershed from 1998 to 2000, the results show that soil moisture distributions were related to the gully positions. Of the three geomorphologic parts of the gully watershed, the moisture on the upland was the highest, in between was the gully floor and gully side slope. Water content on the gully side ‘pipe’ was the dryest, close to the wilting point. No matter what position, soil moisture varied in different depths and in different years. Surface layers were more sensitive to the rainfall than deep layers and so soil moisture of the shallow layers changed greatly, higher in rainfall periods or a wet year and lower in dry periods or a dry year. It was noted that water content was very stable throughout 1998—2000 for both gully side ‘pipe’ and the deeper layers especially deeper than 200cm. They were different in that deep layers had a slight higher soil moisture content and gully side ‘pipe’ was extremely dry. Rainfall was the only water source for the soil moisture in the study area, and the depth to which rain water penetrated was different and in accordance with rainfall. In a wet year, the penetration depth was down to 100cm—120cm deep, but only down to 40cm—50cm in a dry year.

The runoff generation in the gully watershed depended greatly on the rainfall features. The runoff generally occurred if the maximum 5-minute rainfall intensity exceeded 30mm/hr. The runoff hydrograph rise was short, 3—5 minutes, but its decline took longer, 5—16 minutes.

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