Development of Rill Erosion On Bare Sloping Farmland Under Natural Rainfall Conditions

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Abstract

Rill erosion is an important type of soil erosion and provide a basis for preventing and controlling soil loss on sloping farmland. This study was conducted in a standard runoff plot of bare soil (20 m length, 5 m width with a slope of 10 degrees) to monitored runoff and sediment processes during two continuous and two intermittent natural rainfall events, and observed the rill morphological characteristics after multiple rainfall conditions. We observed the runoff and sediment processes presented a pattern of multi-peaks for continuous rainfall events, and a pattern of single or two peaks during two intermittent rainfall events. The sediment yield rate with instantaneous rainfall intensity and runoff rate exhibited a peak lag phenomenon with 1–6 min. After multiple rainfall events, rill were identified as strip-shaped, V-shaped, and tree-branched distribution, and rills were mainly distributed in 5–20 cm width and 0–10 cm depth, and the mean rill length, width and depth increased 2.27, 0.30 and 0.16 times compared to the initial slope (R_0). The side-wall collapse erosion was mostly greater than downcutting erosion in the slope section I, II and III. In conclusion, this study help to understanding the slope runoff and erosion mechanisms, and provide a scientific basis for soil erosion model on sloping farmland.

Introduction

Soil erosion is a serious problem to the environment globally (Ochoa-Cueva et al. 2013; Gao et al. 2016), leading to soil nutrient loss (Shi et al. 2018), land degradation (Mwango et al. 2014; Xu et al. 2016), and significantly impacting agricultural and environmental sustainability (Montgomery 2007; Kimaro et al. 2008). Sloping farmland has been recognized as the main area of soil erosion and water loss (He et al. 2013; Lenka et al. 2017). Therefore, it is important to prevent and control the soil and water loss for sloping farmland.

Rainfall is the main factor driving soil and water loss on sloping farmland (Cuomo and Della Sala 2013; Montenegro et al. 2013). Rainfall is divided into continuous and intermittent rainfall patterns (Fohrer et al. 1999). Continuous rainfall is a single rainfall event, which encompasses a combination of different rainfall intensities that vary with rainfall duration (Zheng et al. 2016), and the intermittent rainfall with sequential rainfall events. Runoff and sediment transport are the importance processes of water erosion, which usually increase with increasing rainfall intensity (Assouline and Ben-Hur 2006). Most existing studies have focused on the processes of runoff and sediment under simulated rainfall conditions, and analyzed the effect of land use on annual runoff and soil loss under natural rainfall conditions (Zhao et al. 2014; Zhao and Hou 2018; Liu et al. 2019; Prats et al. 2014; Chen et al. 2018; Zhang et al. 2020). However, the dynamic process of runoff and sediment on sloping farmland under varying natural rainfall patterns was not clear.

Rill formation and development have a major impact on runoff and sediment processes (Shen et al. 2016). Rill topography is essential for controlling runoff velocity and sediment yield (Giménez and Govers 2001; Mahmoodabadi et al. 2014). Runoff and sediment yield increase when rills are present (He et al. 2017; Xiao et al. 2017; Luo et al. 2018). A large number of experiments have been carried out to study the process of rill erosion. A previous study found that small drop pits represented the beginning of rill erosion during rainfall (Zheng et al. 1987), when the rainfall runoff erosive force exceeding a certain threshold of soil resistance, rills begin to form and develop. Based on the time for rill occurrence, rill erosion processes is grouped into five stages: knick points, headcut extension, intermittent rill, continuous rill, and rill networks under a multi-rainfall condition (Huo et al. 2011). Rill erosion also is a complex physical process that includes headcut advance, bed incision (downward scouring) and sidewall expansion (widening) (Qin et al. 2019).

Complex rill erosion processes are described by the morphological characteristics (Di Stefano and Ferro 2011; Yan et al. 2011). Basic rill morphological indicators mainly including rill length, width, and depth (Bewket and Sterk 2003; Raff et al. 2004). Rill length is usefully chosen to describe the rill process (Bruno et al. 2008), rill width and depth are measured to evaluate the erosion rate (Cerdan et al. 2002). Meanwhile, rill density is used to characterize the erosion process (Gilley

et al. 1990). The mean density, depth, and width of rills can be used to describe the development of rill erosion (Ran et al. 2018). The bifurcation ratio and node reflect the diversity of rill network structures with high sensitivity (Zhang et al. 2015). Previous studies about the rill erosion mainly focused on the simulated artificial rainfall conditions (Jiang et al. 2019), scouring experiment (Huang et al. 2020; Niu et al. 2020) and combination of rainfall and inflow experiment (Tian et al. 2017). However, the processes of rill erosion has rarely been observed after multiple natural rainfall events, and compare to the variation of rill morphological indicators. Therefore, it is necessary to monitor rill morphology on sloping farmland under natural rainfall conditions for predicting soil erosion.

Rill erosion characteristics also have various erosion patterns in different slope sections. As rainfall intensity increases, sediment detachment in downslope sections is influenced by upslope runoff and sediment concentration, and concentrated erosion on rills (Luk et al. 1993; Paroissien et al. 2010). A rill erosion research was measured in three slope surface sections, the upper slope section with a small catchment area, weak runoff erosion, and small rills; the second slope section includes the confluence and lateral overflow of rills in the upper slope section; the third slope section has less rill bifurcation, resulting in the continued strengthening of runoff concentration (Shen et al. 2014). However, although the rill erosion research on different slope sections remains a pressing concern, but there is little information on rill erosion of various slope sections during the mutiple natural rainfall conditions.

This study objectives included to: (1) analyze runoff and sediments processes during different rainfall patterns; (2) examine how the change (increment or decrement) of main rill morphological variables after multiple rainfall events; and (3) compare the differences of rill morphological parameters for different slope sections on bare sloping farmland. This study provides a scientific basis for erosion mechanisms and to help predict and control soil erosion on sloping farmland.

Materials And Methods

Study area

The study area was located at the Soil and Water Conservation Monitoring Site of Sujiatun District, Shenyang City, Liaoning Province (41°34'N, 123°36'E). This area has a mild and humid climate, with an average annual precipitation and air temperature of 735 mm and 8 °C, respectively (Tang, 2012). The soil type is mainly brown soil as described by the Chinese Soil Classification System (National Soil Survey Office, 1992). The clay content of the soil in the study area is 41.6% (< 0.002 mm), 49.9% silt (0.002–0.05 mm) and 8.5% sand content (> 0.05 mm). Soil bulk density and organic matter were 1.25 g·cm⁻³ and 28.79 g·kg⁻¹, respectively (Zhang et al. 2019). The experiments were conducted in a standard runoff plot of bare soil (20 m length, 5 m width), with a slope of 10 degrees. A fence was placed on the top and both sides of the runoff plot, and a collection tank was set at the bottom of runoff plot for collecting runoff and sediment.

Experimental measurements

Rainfall conditions were observed by an automatic meteorological observatory from July 16 to August 14, 2016, because the most precipitation occurring between July and September. Runoff duration was delineated as the time between the start and end of a runoff event, and measured by a stopwatch. Due to the complexity of natural rainfall conditions, the runoff samples were measured at 1 min or 2 min intervals in the beginning of runoff generation. When runoff duration is nearly 10 min and runoff volume is larger, the sampling interval would be extended to 3 to 4 min. When the rainfall duration was more than 20 minutes, the sampling interval would be extended to 5 to 13 min until the

end of runoff (Reza Vaezi et al. 2020; Zhang et al. 2013). The runoff samples were collected with 1000 ml graduated flask, then sediment samples was oven dried at 105 °C to calculate sediment yield.

Based on rainfall conditions, rills were observed every two rainfall events, and were conducted five times (July 16–August 13, 2016; Table 1). The R_0 was used as the initial value of rill erosion. Rill morphological change of R_1 – R_4 was analyzed by comparing to the initial value.

Table 1. Rill observation conditions on bare soil.

Number	Rainfall date	Precipitation/mm	Rill observation date	Rill observation points
R_0	2016–07–16	–	2016–07–20	36
R_1	2016–07–21	67.0	2016–07–23	54
	2016–07–22	28.0		
R_2	2016–07–25	49.2	2016–07–27	63
	2016–07–26	25.2		
R_3	2016–08–01	5.2	2016–08–02	63
	2016–08–02	0.2		
R_4	2016–08–07	16.4	2016–08–14	63
	2016–08–13	24.6		

Note: “–” denotes no data.

The length, width, depth and locations (x, y) of each rill were manually measured by a steel ruler and tape measure when rills were generated (Li et al. 2020; He et al. 2014). Using the boundary nodes of runoff plot near the rill head as the coordinate origin, the coordinates of main observation points for each rill were determined. In general, a single short rill (< 3 m length) can be described by three observation points at the rill top, center, and bottom. However, the observation points for complex rills had to be encrypted, and the amount of observation points range from 11 to 39, and the measurements intervals along each rill channel range from 1 to 154 cm (Shen et al. 2015a).

Rill morphological characteristics

Rill number represents the sum of the number of rills on the slope for each rainfall event.

Mean rill width (cm) represents the average width of soil erosion on the surface soil for each rainfall event, and reflects the intensity of rill erosion.

Mean rill depth (cm) is the average depth of soil erosion on the surface soil for each rainfall event.

Mean rill length (m) is the average length of soil erosion on the surface soil for each rainfall event, and objectively reflects the distribution of rills on the slope.

Total rill length (m) is the total length of the main rills and secondary rills on the slope.

Rill density (m/m^2) is the total length of all rills in the study area, and reflects the degree of slope fragmentation.

Rill width-depth ratio is the ratio of width to depth, which objectively reflects the change to rill channel shape.

Convergence node is the node at which two or more rills meet during rill development.

Bifurcation node is a node which divided into two or more rills during rill development.

Data analysis

The slope surface of bare soil was divided into three parts on average, including an upper slope section I (0–6.67 m), middle slope section II (6.67–13.34 m), and lower slope section III (13.34–20 m), and three slope sections helped with evaluating the variation of rill parameters. Origin 2017 was used to draw the runoff and sediment processes, rill width and depth frequency distribution, along with the changes of main rill morphological parameters in the different slope sections. AutoCAD 2014 software was used to draw the rill type and morphology of bare soil after multiple rainfall events.

Results

Rainfall conditions, runoff, and sediment loss

Eight rainfall events were observed in the experiment (Table 2). Four of these events generated runoff, two of which were continuous rainfall pattern, while the other two were intermittent rainfall pattern. Intermittent rainfall represents multiple rainfall events in a day, whereas continuous rainfall represents only one rainfall event in a day.

Table 2 Rainfall conditions.

Date	Precipitation (mm)	Average rainfall intensity (mm·min ⁻¹)	Rainfall pattern
2016–07–21	67.0	0.08	Intermittent rainfall
2016–07–22	28.0	0.04	Continuous rainfall
2016–07–25	49.2	0.04	Intermittent rainfall
2016–07–26	25.2	0.03	No runoff initiation
2016–08–01	5.2	0.02	No runoff initiation
2016–08–02	0.2	0.10	No runoff initiation
2016–08–07	16.4	0.05	No runoff initiation
2016–08–13	24.6	0.06	Continuous rainfall

The duration of runoff was the same as sediment yield during two continuous rainfall events. The variation of sediment yield were similar to runoff volume during two intermittent rainfall events, four runoff and sediment processes were recorded during the first rainfall event, with runoff duration of 24, 18, 7, and 14 min, respectively (Table 3). Runoff volumes were higher in the second runoff process compared to the first runoff process. The first two runoff and sediment yield accounted for 81% and 81% of total runoff and sediment yield, respectively. For the second intermittent rainfall event, runoff volumes were higher in the first runoff process compared to the second runoff process. The first two runoff and sediment yield accounted for 95% and 97% of total runoff and sediment yield, respectively.

Table 3 Runoff and sediment conditions.

Date	Runoff and sediment duration (minutes)	Runoff (L)	Sediment (g)	Runoff percentage (%)	Runoff percentage (%)
2016-07-22	49	679	14322		
2016-08-13	32	816	34733		
2016-07-21	24	60	1437	18	16
	18	208	5700	63	65
	7	36	801	11	9
	14	28	822	8	9
	63	332	8760	100	100
2016-07-25	22	1069	70732	88	88
	7	87	7635	7	9
	12	57	2274	5	3
	41	1213	80641	100	100

Characteristics of runoff and sediment processes

The runoff and sediment processes with instantaneous rainfall intensity presented a pattern of multi-peaks (2 or 4 peaks) during two continuous rainfall events. For the first continuous rainfall event (Fig. 1a), the first peak value of rainfall intensity occurred at 3 min, and the first sediment yield rate at 5 min. The second peak in rainfall intensity occurred at 13 min, with runoff rate starting 2 min before (at 11 min). However, the runoff and sediment processes not have a lag in peak with rainfall intensity during the second continuous rainfall event (Fig. 1b).

For the two intermittent rainfall events, runoff processes with instantaneous rainfall intensity presented the pattern of single peak or two peaks (Figs. 2–3). The first intermittent rainfall event had four runoff processes (Fig. 2). In the first runoff process (Fig. 2a), rainfall intensity peaked at 1 min, while runoff and sediment yield rate peaked at 7 min. Runoff and sediment yield rate peaked 4 min earlier than rainfall intensity during second runoff process (Fig. 2b). For the third runoff process (Fig. 2c), rainfall intensity peaked at similar time as runoff and sediment yield rate. Rainfall intensity, runoff rate, and sediment yield rate peaked at 4, 6, and 4 min during the fourth runoff process (Fig. 2d).

Compared to the first rainfall event, three runoff processes were produced during the second intermittent rainfall event (Fig. 3). During the first runoff process (Fig. 3a), rainfall intensity peaked at 2 min and 14 min, while runoff and sediment yield rate reached the first peak, and peaked at 14 min. During the second runoff process (Fig. 3b), rainfall intensity peaked at 2 min, and runoff and sediment rate peaked at 1 min. During the third process (Fig. 3c), rainfall intensity, runoff, and sediment yield rate peaked at 4, 3, and 3 min, respectively. Sediment yield rate peaked at 11 min again, while runoff rate peaked 2 min earlier.

Rill morphological characteristics after multiple rainfall events

Rill morphological distribution on bare soil was shown in Fig. 4. Three rill types were identified as strip-shaped, V-shaped, and tree-branched distribution. Rill number increased significantly, and rill morphology gradually evolved from narrow strip to wide strip along the direction of rill head after four rill events (R_1 – R_4). There were seven rills on the initial rill slope (R_0), five of which were strip-shaped and V-shaped, and two of which were tree-branched distribution. In the first rill event (R_1), the initial three (strip or V-shaped) rills merged with the two main rills to form a concentrated flow path, and a new rill with tree-branched distribution was generated, the total number of rills declining to five. With the occurrence of headward erosion, the new rills adjacent to the upper and lower branches connected to the main rills and intensely distributed in the second rill event (R_2). Compared with the second rill event (R_2), some rills were silted by sediment, with five rills being present in the third rill event (R_3). Because of the concentrated flow and headward erosion, more complete rill development was recorded, the silted rills in the third rill event (R_3) connected with the main rills again in the fourth rill event (R_4).

The frequency distribution of rill width and depth in the five rill events (R_0 – R_4) were showed in Fig. 5. Rill width was classified as six groups (0–5 cm, 5–10 cm, 10–15 cm, 15–20 cm, 20–25 cm, and > 25 cm) based on the data of rill width, rill depth was classified as 0–5 cm, 5–10 cm, and 10–15 cm. Rill width mainly ranged from 5 to 20 cm in the five rill events (R_0 – R_4), and their proportions to the total rills were 88.89%, 85.19%, 84.13%, 85.71% and 85.72%, respectively. Rills were mainly distributed in 0–10 cm depth in four rill events (R_1 – R_4), and the frequencies were 100.00%, 98.15%, 100.00%, 98.41% and 98.41%, respectively.

The rill parameters of bare soil in the five events (R_0 – R_4) were shown in Table 4. After the four rill events (R_1 – R_4), the range of rill length, width and depth were 1.45–51.57 m, 7.00–18.25 and 3.15–5.75 cm, respectively. The total and mean rill length increased 0.87 and 2.27 times compared to the initial slope (R_0), as well as the mean rill width and depth increased 0.30 and 0.16 times. Mean rill length and depth showed similar trends, and rill erosion mainly reflected the variation of rill length. Rill density and width-depth ratio ranged from 0.44 to 0.83 cm and 1.73 to 2.88, respectively. The range of rill convergence and bifurcation node was 6.00–15.00 and 1.00–4.00, respectively. After the four rill events, the trend of rill density increased 0.89 times compared to the initial slope (R_0), the convergence and bifurcation node also showed an increasing trend but the width-depth ratio in an opposite trend.

Table 4 The Changes of rill parameters on bare soil.

	R0	R1	R2	R3	R4
l_{total}	44.17	74.65	81.61	74.2	82.59
l_{mean}	6.31	14.93	20.40	14.84	20.65
l_{range}	1.45–16.70	1.45–44.06	1.45–50.56	1.45–45.77	1.45–51.57
W_{mean}	11.15	10.06	12.81	13.42	14.51
W_{range}	7.00–16.67	7.50–12.00	11.27–14.48	11.50–16.25	11.00–18.25
h_{mean}	4.09	4.53	4.71	4.31	4.73
h_{range}	3.15–5.75	4.00–5.15	4.35–5.13	3.25–4.75	4.35–5.23
ρ	0.44	0.75	0.82	0.74	0.83
d/h	2.88	2.23	1.73	1.90	1.88
c	6.00	10.00	15.00	13.00	14.00
b	1.00	3.00	4.00	2.00	3.00

Note: l_{range} , W_{range} , and h_{range} are the range of rill length, rill width, and rill depth, respectively; l_{mean} , W_{mean} , and h_{mean} are the mean value of rill length, rill width, and rill depth, respectively; l_{total} is the total length of rill. Rill density: ρ ; Rill width-depth ratio: W/h ; convergence node : c ; Bifurcation node: b .

Variation of rill morphological parameters in different slope sections

The upper slope section I (0–6.67 m) was located at the upper part of bare soil, with the belt of no erosion was 0.75 m, the belt of no erosion was an area at the top of each slope that is not dissected by rills (Horton, 1945). The upper slope surface was flat with no protection from vegetation, flow was relatively uniform, and runoff erosion force was weak, while rills were densely and evenly distributed.

Compared to the slope section II (6.67–13.34 m) and III (13.34–20 m), rill density of the upper slope section I was largest (Table 5). Middle slope section II had the greatest rill number, followed by I and III. Due to the concentrated flow in the upper slope section, rills bifurcated and merged, resulting in the increased of rill number in the middle slope section II. In the lower slope section III, the rill density and number were generally lower than the other slope sections. The variation of rill width was more significant than rill depth (Fig. 6), and the value of width-depth ratio >1 , indicated that side-wall collapse erosion was greater than downcutting erosion for the three slope section in the five rill event (except for the slope section III in the fourth rill event). The variation of rill width and depth was highly obvious in middle slope section II, thus the slope section II was the most active area of rill erosion development. Because of the confluence of runoff and sediment from the upper slope section I to the lower slope section III, runoff and sediment silting reduced the rill depth to the minimum value in the lower slope section III, thus the slope section III was the sediment deposition area.

Table 5 Rill number, density and width-depth ratio of different slope sections in five rill events.

Rainfall events	Rill number			Rill density(m·m ⁻²)			Rill width-depth ratio		
	I	II	III	I	II	III	I	II	III
R ₀	5	5	2	0.77	0.41	0.14	3.72	2.72	1.55
R ₁	4	5	3	0.90	0.87	0.48	3.36	1.97	1.75
R ₂	4	5	2	0.90	0.89	0.66	2.96	1.99	2.19
R ₃	5	5	3	0.82	0.87	0.54	4.11	2.05	2.49
R ₄	4	4	2	0.90	0.89	0.69	2.76	2.60	0.88

Discussion

Characteristics of runoff and sediment processes

Rainfall characteristics (Almeida et al. 2020), soil moisture conditions (Fortesa et al. 2020), soil crust (Carmi and Berliner 2008), slope features (Fu et al. 2011) and vegetation coverage (Duan et al. 2016) have a great influence on surface runoff and sediment loss. Sediment loss depended on the runoff detachment and transport capacity (Vaezi et al. 2017). Runoff is the major external factor leading to erosion and the carrier of sediment (Peng et al. 2014).

During the first continuous rainfall event, the time to first peak of runoff rate was same as rainfall intensity, but sediment yield rate peaked 2 min later than runoff. This may due to the energy of surface runoff is not sufficient to initiate movement of soil particles and only transported the pre-detached soil particles in rainfall-induced erosion (Kinnell, 2005). In addition, rill erosion and slope condition also influenced the sediment yield. Consequently, sediment yield peaked later than runoff and rainfall intensity.

During the first intermittent rainfall event, runoff volume was higher during the second runoff process compared to the first runoff process. Because of the antecedent rainfall, the already existing soil moisture content was more than the initial value, soil infiltration capacity decreased, and the runoff depth increased, the similar rainfall intensity leading to greater runoff volume (Erpul and Canga 1999; Sadeghi et al. 2016). However, runoff volume was lower owing to the low rainfall intensity during the second runoff process than the first runoff process for the second intermittent rainfall event.

For intermittent rainfall events, the time to peak runoff and sediment yield rate was later than rainfall intensity during the first runoff process. Soil surface was dry without previous rainfall, the initially large rainfall intensity forming a temporary and relatively impermeable layer, thus surface runoff and sediment showed a clear peak lag phenomenon (Liu et al. 2002). However, the time to peak runoff rate was equal to or earlier than that of rainfall intensity during the other runoff process, the reason was that previous rainfall had moistened the soil, infiltration rate decreased with increased rainfall intensity, and the soil gradually became saturated. As a result, runoff generation time shortened and peaked earlier gradually (Zhang et al. 2018).

Rill morphological characteristics

Rill erosion is a complex processes, including drop-pits (Dong et al. 2016; Zhao et al. 2017), headward erosion (Kohl 1988; Zhu et al. 1995), rill side-wall collapse (Oygarden 2003), micro-rill (Torri and Brya 1997), continuous rills, downcutting erosion (Hagerty 1991), and rill bifurcation and convergence (Tian et al. 2017). In this study,

rill morphological development of bare soil mainly driven by runoff convergence, headward erosion, side-wall collapse, downcutting erosion, and rill adjustment (bifurcation and convergence).

Three rill types of bare soil were detected: strip-shaped, V-shaped, and tree-branched distribution. Due to the runoff convergence effect, intermittent strip-shaped rills merged to form V-shaped rills. Then continuous rills with tree-branched distribution were formed by runoff convergence and headward erosion. Similarly, Rahma et al. (2017) showed that intermittent rills (strip-shaped) and multiple rills (tree-branched distribution) formed in sand and clay covered by straw.

After multiple nature rainfall events (two days rainfall range from 95 to 215.8 mm), rills were mainly distributed in the range of 5–20 cm width and 0–10 cm depth. A similar result was reported by Guo et al. (2019), the rills with a 5–20 cm width and a 0–15 cm depth following torrential rain (200 mm rainfall) on sloping farmland.

The mean rills length, width, and depth of bare soil showed an increase trend after four rill events, the change were driven mainly by the rainfall condition, lack of vegetation cover and loose surface soil. After multiple rainfall events, soil particles were gradually denuded, thus aggravate the rill erosion (Cerdan et al. 2010). Headward erosion and connections of a few rills on the same concentrated flow path caused a rapid increase of rill length on bare soil (Zhang et al. 2017). Rill width-depth ratio ranged from 1.73 to 2.88, which meant that the side-wall collapse rate of rills was higher than the downcutting erosion of rills (Guo et al. 2019).

Rill parameters of different slope sections on bare soil

Usually, rill development is preceded by a belt of no erosion, with the area needed for rill initiation being 5–10 m (Torri et al. 1999). A similar result was reported by Rejman and Brodowski (2005). The absence of a belt of no erosion could be located in the middle part of the slope during the storm event. However, our study found that the belt of no erosion was 0.75 m after four rill events, because of the different slope and rainfall conditions.

After the four rill events (R_1 – R_4), side-wall collapse erosion was mostly greater than downcutting erosion in the slope section I, II and III. The variation of rill width and depth was highly obvious in middle slope section II, thus the slope section II was the most active area of rill erosion development. In the lower slope section III, the mean rill depth decreased because of the presence of depression areas in the lower slope (Gessesse et al. 2015). The runoff and sediment convergence from the slope section I to the lower slope section III, resulted in decreased transport capacity of runoff and increased runoff and sediment silting, which was mainly reflected in a decline of rill depth (Quan et al. 2020).

When runoff generated on the slope surface, the occurrence and development of rills are not recorded by camera, and the rill erosion development was observed only by ruler method. Thus, future studies should evaluate the rill erosion processes and changes on sloping farmland by new technology, such as 3D-PR technology (Di Stefano et al. 2017), photogrammetry and micro-topography (Ran et al. 2018).

Conclusions

This study evaluated runoff, sediment, and the morphological characteristics of rills on bare sloping farmland for multiple natural rainfall events. The sediment processes with instantaneous rainfall intensity and runoff had a lag in peak timing during two continuous and two intermittent natural rainfall events. Runoff volumes were higher in the second runoff process compared to the first runoff process during intermittent rainfall events. Rill erosion development was mainly reflected in the increase of rill length, but the width-depth ratio in an opposite trend. Rills were mainly distributed in the range of 5–20 cm width and 0–10 cm depth. The slope section II (6.67–13.34 m) was the main active

area of rills development, the lower slope section III (13.34–20 m) was the sediment deposition area. This study provide a basis for future studies on rill erosion and need to control upslope runoff and sediment in agricultural areas.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication The studied participant consent for publication.

Availability of data and materials The material and data are available upon request.

Competing interests The authors declare that they have no competing interests.

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Authors'contributions Jingling Zhang analyzed and wrote the first draft of the manuscript. Lili Zhou and Donghao Huang did critical revision of the manuscript. All authors read and approved the final manuscript.

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Figures

Figure 1

Characteristics of runoff and sediment processes during continuous rainfall events.

Figure 2

Characteristic of runoff and sediment processes during the first intermittent rainfall event.

Figure 3

Characteristic of runoff and sediment processes during the second intermittent rainfall event.

Figure 4

Distribution of rills on bare soil during five rill events (R0–R4); A: strip-shaped; B: V-shaped; C: tree-branched distribution.

Figure 5

Frequency distribution of rill width and depth in the five rill events (R0–R4).

Figure 6

Changes of rill width and depth with unit slope length