Development of rill erosion on bare sloping farmland under natural rainfall conditions

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Abstract
Rill erosion plays an important role in soil erosion, and studying this process can provide a basis for controlling soil loss on sloping farmland. The objectives of this study were to observe runoff and sediment transport processes during two continuous and two intermittent natural rainfall events and to monitor the changing morphological characteristics of rills within a standard runoff plot of bare soil (20 m length, 5 m width, and slope of 10°) at five successive observation times. We found that the processes of runoff and sediment transport presented a pattern with multiple peaks during continuous rainfall events and with a single or two peaks during intermittent rainfall events. The peak runoff and sediment yield rates exhibited a time-lag phenomenon of 1–12 min compared with instantaneous rainfall intensity. Rills occurred as strip-shapes, V-shapes, and with a tree-branch-like distribution; their widths were mainly 5–20 cm and their depths 0–10 cm. Compared to our initial rill observation, the mean rill length, width, and depth increased by 227%, 26%, and 6%, respectively, after four subsequent rill observations over a period of almost one month. Side-wall collapse erosion was greater than downcutting erosion on the middle slope (section II; 6.67–13.34 m), while rill depth reached a minimum value on the lower slope (section III; 13.34–20 m). These findings help us to understand bare slope runoff and erosion mechanisms and provide a scientific basis for soil erosion modeling of sloping farmland.

Keywords Continuous natural rainfall · Intermittent natural rainfall · Runoff processes · Rill morphology

Introduction
Soil erosion is a serious global environmental problem (Borrelli et al. 2017), leading to soil nutrient loss (Shi et al. 2018), land degradation (Xu et al. 2016), and marked impacts on agricultural sustainability (Montgomery 2007). Sloping farmland has been recognized as a main area of soil erosion and water loss (Li et al. 2019). Therefore, it is important to prevent and control soil and water loss from sloping farmland.

Runoff and sediment transport, important processes that control soil erosion, usually increase with increasing rainfall intensity (Wu et al. 2018a; Liang et al. 2020). Existing studies have focused on the processes of runoff and sediment transport under simulated rainfall conditions and have analyzed the effect of land use on annual runoff and soil loss under natural rainfall conditions (Zhao and Hou 2018; Liu et al. 2019; Chen et al. 2018; Zhang et al. 2020). However, the dynamic processes of runoff and sediment transport on sloping farmland under varying natural rainfall patterns remain unclear.

Rill formation and development has a major impact on runoff and sediment transport processes. Runoff and sediment yield increase when rills are present (He et al. 2017). A number of studies have investigated the process of rill erosion. For example, Zheng et al. (1987) found that small drop pits represented the beginning of rill erosion; when the rainfall runoff erosive force exceed a certain threshold of soil resistance, rills began to form and develop. Huo et al. (2011) classified rill erosion processes into five stages based on the time of rill occurrence; these included knick points, headcut extension, intermittent rill, continuous rill, and rill networks, under a multi-rainfall condition. Qin et al. (2019) showed that rill erosion was a complex physical process, including
headwall expansion (widening). Sun et al. (2021) reported that rill erosion processes could be reasonably described using seven stages: splash and sheet erosion, drop pits, head-cut erosion, intermittent rill, continuous rill, rill network development, and transition from rill to ephemeral gully on a convex slope.

Complex rill erosion processes are described using morphological characteristics (Di Stefano and Ferro 2011). Basic rill morphological indicators include 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), whereas rill width and depth are measured to evaluate the erosion rate (Cerdan et al. 2002). Meanwhile, the mean density, depth, and width of rills can be used to describe the development of rill erosion (Ran et al. 2018). Moreover, the bifurcation ratio and node can reflect the diversity of rill network structures with high sensitivity (Zhang et al. 2015). Most previous studies have described rill erosion under various experimental conditions, such as artificial rainfall (Jiang et al. 2019), scouring experiments (Huang et al. 2020; Niu et al. 2020), and combination of rainfall and inflow experiments (Tian et al. 2017). However, few studies have observed the processes of rill erosion during and after multiple natural rainfall events.

Rill development shows different erosion patterns in different sections of a slope. Upslope runoff and sediment convergence have an important effect on the behavior of downslope sections (Luk et al. 1993; Xu et al. 2017). Rill development on a slope surface can be divided into three slope sections: the upper slope (section I) having small rills and weak runoff erosion; the middle slope (section II) experiencing upslope runoff convergence and lateral overflow; and the downslope region (section III) having less rill bifurcation and strong runoff convergence (Shen et al. 2014). However, although rill erosion research on different slope sections remains a pressing concern, there is little available information regarding rill erosion on the various slope sections during natural rainfall conditions.

Therefore, the main objectives of this study were as follows: (1) analyze runoff and sediment transport processes during continuous and intermittent rainfall events; (2) examine how the main rill morphological indicators change after multiple rainfall events; and (3) compare the variation of rill morphological indicators on different slope sections of bare sloping farmland.

Materials and methods

Study area

The study site was located within the Soil and Water Conservation Monitoring Station of Suijatun, Shenyang, Liaoning Province (41° 34′ N, 123° 36′ E). This area has a mild and humid climate, with an average annual precipitation of 735 mm and air temperature of 8 °C (Tang 2012). The brown soil has been described by the Chinese Soil Classification System (National Soil Survey Office 1992). The proportions of clay (<0.002 mm), silt (0.002–0.05 mm), and sand (0.05–2 mm) content in the soil were 41.6%, 49.9%, and 8.5%, respectively. Soil bulk density and organic matter content were 1.25 g cm\(^{-3}\) and 28.79 g kg\(^{-1}\), respectively (Zhang et al. 2019). Experimental measurements

Table 1  Rainfall conditions

| Date       | Rainfall amount (mm) | Rainfall pattern          |
|------------|----------------------|----------------------------|
| 2016–07–21 | 67.0                 | Intermittent rainfall     |
| 2016–07–22 | 28.0                 | Continuous rainfall       |
| 2016–07–25 | 49.2                 | Intermittent rainfall     |
| 2016–07–26 | 25.2                 | No runoff initiation      |
| 2016–08–01 | 5.2                  | No runoff initiation      |
| 2016–08–02 | 0.2                  | No runoff initiation      |
| 2016–08–07 | 16.4                 | No runoff initiation      |
| 2016–08–13 | 24.6                 | Continuous rainfall       |
sediment samples were oven dried at 105 °C to calculate the sediment yield.

Based on rainfall conditions, we made rill observations after every two rainfall events. A total of five observations were made, including an initial and four subsequent rill observations (Table 2). The length, width, depth, and locations (x, y) of each rill were manually measured using a steel ruler and tape measure when the rills were generated (Li et al. 2020; He et al. 2014). Using the boundary nodes of the runoff plot near the rill head as the coordinate origin (0, 0), the coordinates of each of the main observation points were determined for each rill. In general, a single short rill (< 3 m length) could be described by three observation points at the rill top, center, and bottom, whereas the observation points for complex rills had to be encrypted. The number of observation points for a complex rill ranged from 11 to 39. The measurement intervals ranged from 1 to 154 cm along the slope surface (Shen et al. 2015).

**Rill morphological characteristics**

The rill morphology indicators included rill number, mean rill width, depth and length, total rill length, rill density, width–depth ratio, convergence node, bifurcation node, and a belt of no erosion (Table 3).

**Data analysis**

Rill width was classified into six groups (0–5, 5–10, 10–15, 15–20, 20–25, and > 25 cm), and rill depth was classified into three groups (0–5, 5–10, and 10–15 cm) based on our rill observation data. The slope surface of bare soil was divided into three parts: 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), which could then be used in the evaluation of the variation of rill parameters. *Origin 2017* software was used to construct the runoff and sediment transport processes, rill width and depth frequency distributions, and document changes in the main rill morphological parameters in the different slope sections. *AutoCAD 2014* software was used to illustrate rill types and morphologies after multiple rainfall events.

**Results**

**Runoff and sediment loss**

Four runoff and sediment transport episodes were recorded during the first intermittent rainfall event (an initial rainfall and three subsequent rainfalls), with runoff durations of 24, 18, 7, and 12 min, respectively (Table 4). Runoff volumes were higher during the first subsequent rainfall than during the initial rainfall. The first two runoff volumes and sediment yields accounted for 79.42% and 81.92% of total runoff volume and sediment yield, respectively. During the second intermittent rainfall event (an initial rainfall and two subsequent rainfalls), runoff volumes were higher during the

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### Table 2 Rill observation conditions on bare soil

| Number | Rainfall date | Rainfall amount (mm) | Rill observation date | Rill observation points |
|--------|---------------|----------------------|-----------------------|-------------------------|
| Initial | 2016–07–16    | ~                    | 2016–07–20            | 35                      |
| 1st     | 2016–07–21    | 67.0                 | 2016–07–23            | 53                      |
|         | 2016–07–22    | 28.0                 |                       |                         |
| 2nd     | 2016–07–25    | 49.2                 | 2016–07–27            | 62                      |
|         | 2016–07–26    | 25.2                 |                       |                         |
| 3rd     | 2016–08–01    | 5.2                  | 2016–08–02            | 62                      |
|         | 2016–08–02    | 0.2                  |                       |                         |
| 4th     | 2016–08–07    | 16.4                 | 2016–08–14            | 62                      |
|         | 2016–08–13    | 24.6                 |                       |                         |

“−” denotes no observation data

### Table 3 Descriptions of rill morphology indicators

| Indicators              | Significance                                                                 |
|-------------------------|-----------------------------------------------------------------------------|
| Rill number             | The sum of the number of rills on the slope surface                         |
| Mean rill width (cm)    | The average width of soil erosion and rill erosion intensity on the slope surface |
| Mean rill depth (cm)    | The average depth of soil erosion on the slope surface                       |
| Mean rill length (m)    | The average length of soil erosion; reflects the distribution of rills on the slope surface |
| Total rill length (m)   | The total length of main rills and secondary rills on the slope surface       |
| Rill density (m⁻²)      | The total length of all rills; reflects the degree of slope fragmentation    |
| Rill width–depth ratio  | The ratio of width to depth; reflects changes to rill channel shape           |
| Convergence node        | A node at which two or more rills meet during rill development               |
| Bifurcation node        | A node which divides into two or more rills during rill development          |
| Belt of no erosion      | An area at the top of each slope that is not dissected by rills (Horton 1945) |
initial rainfall than during the first subsequent rainfall. During this event, the first two runoff volumes and sediment yields accounted for 95.29% and 97.18% of total runoff volume and sediment yield, respectively.

Characteristics of runoff and sediment transport processes

Runoff and sediment transport processes varied with instantaneous rainfall intensity and presented a pattern with multiple peaks (2 or 4 peaks) during the two continuous rainfall events. For the first continuous rainfall event (Fig. 1a), the first peak value of rainfall intensity and runoff occurred at 3 min, and the first peak sediment yield rate occurred at 5 min. The second peak of rainfall intensity and sediment yield occurred at 13 min, but the peak runoff rate started 2 min before (at 11 min). However, the peak runoff and sediment yield rates showed no time-lag phenomenon with rainfall intensity during the second continuous rainfall event (Fig. 1b).

During the two intermittent rainfall events, runoff and sediment transport processes varied with instantaneous rainfall intensity and presented a pattern with either a single peak or two peaks (Figs. 2 and 3). For the first intermittent rainfall event (Fig. 2), rainfall intensity peaked at 1 min, while runoff and sediment yield rates peaked at 7 min during the initial rainfall (Fig. 2a); runoff and sediment yield rates then peaked 4 min earlier than rainfall intensity during the first subsequent rainfall (Fig. 2b). Rainfall intensity peaked at the same time as runoff and sediment yield rates during the second subsequent rainfall (Fig. 2c). Rainfall intensity, runoff rate, and sediment yield rate peaked at 4, 2, and 4 min, respectively, during the third subsequent rainfall (Fig. 2d).

Three runoff episodes were generated during the second intermittent rainfall event (Fig. 3). Rainfall intensity peaked at 2 min and 14 min, while runoff and sediment yield rates reached their first peak at 14 min during the initial rainfall (Fig. 3a). Rainfall intensity, runoff and sediment yield rates peaked at 1 min during the first subsequent rainfall (Fig. 3b). For the second subsequent rainfall (Fig. 3c), rainfall intensity, runoff rate, and sediment yield rate peaked at 4, 3, and 3 min, respectively. Rainfall intensity and runoff rate showed a second peak at 9 min, while for sediment yield rate this second peak occurred at 10 min.

Rill morphological characteristics after multiple rainfall events

The distribution of rill morphologies on bare soil is shown in Fig. 4. Three rill types were identified: strip-shaped,
V-shaped, and those with tree-branch-like distributions. Rill number increased markedly, and rill morphology gradually evolved from a narrow strip to a wide strip along the direction of rill head, as we moved from our initial rill observation through our four subsequent rill observations. There were seven rills on our initial rill observation (Fig. 4a), including three strip-shaped rills, two V-shaped rills, and two rills with a tree-branch-like distribution. At the first subsequent rill observation (Fig. 4b), three of the initial rills (strip or V-shaped) had merged with the two main rills to form a concentrated flow path, and a new rill with a tree-branch-like distribution had been generated; the total number of rills had decreased to five. With the occurrence of headward erosion, new rills adjacent to the upper branches connected to the main rills had developed by the time of our second subsequent rill observation (Fig. 4c). Five rills were present at our third subsequent rill observation (Fig. 4d), indicating that some rills had been silted by sediment between our second and third observations. Because of concentrated flow and headward erosion, the silted rills seen at our third subsequent rill observation had reconnected with the main rills by the time of our fourth subsequent rill observation (Fig. 4e).

The frequency distributions of rill width and depth at our initial and four subsequent rill observations are shown in Fig. 5. Rill widths (Fig. 5a) mainly ranged from 5 to 20 cm, making up 88.57%, 84.91%, 85.48%, 85.48%, and 85.48% of the total rills at the five successive observation times. Rills were mainly 0–10 cm in depth, making up 100.00%, 98.11%, 100.00%, 98.39%, and 98.39% of the total rills at the five successive observation times (Fig. 5b).

The ranges of rill lengths, widths, and depths were 1.45–51.57 m, 7.00–18.25 cm, and 3.15–9.00 cm, respectively (Table 5). The total rill length, mean rill length, mean rill width, and mean rill depth increased by 87%, 227%, 26%, and 6%, respectively, between our initial and fourth subsequent rill observation over a period of almost one month. Rill density, convergence, and bifurcation node showed similar trends of increase, but the width–depth ratio decreased. The belt of no erosion remained at 0.75 m over the entire rill observation period.

**Variation of rill morphological parameters in different slope sections**

Rill number was higher in slope sections I and II than in section III (Table 6). Rill density was greater in section I than in sections II and III. Rill width showed a greater variability than rill depth (Fig. 6). Rill width–depth ratios of > 1
indicated that side-wall collapse erosion was greater than downcutting erosion in all rill observations (except for slope section III in the fourth subsequent rill observation, Table 6). A higher variability in rill width and depth occurred in slope section II than in the other slope sections, while rill depth reached a minimum value in slope section III.

**Discussion**

**Characteristics of runoff and sediment transport processes**

Runoff volume and sediment yield was higher during the first subsequent rainfall than during the initial rainfall in the first intermittent rainfall event. This finding is consistent with Yadav and Watanabe (2018), who found that the amount of cumulative runoff was significantly greater during a second rainfall compared with the first. This is because of the antecedent rainfall, which increases the soil moisture above its initial value, decreases soil infiltration capacity, and leads to a similar rainfall intensity creating greater runoff volume and sediment yield (Sadeghi et al. 2016). In contrast, during the second intermittent rainfall event, runoff volume and sediment yield was higher during the initial rainfall than during the first subsequent rainfall; this may be due to the low intensity of the first subsequent rainfall (Fig. 3b).

During the first continuous rainfall event, we found that the time to the first peak of runoff rate was the same as peak rainfall intensity, but the sediment yield rate peaked later than the runoff rate. When rainfall begins, soil infiltration capability gradually decreases with increasing rainfall and soil crust formation. When soil moisture reaches saturation, or the rainfall intensity is greater than the soil infiltration rate, the soil surface begins to generate runoff (Wang et al. 2021). In our study, antecedent rainfall (on July 21) may have led to wetter soil and soil crust formation; coupled with heavy rainfall intensity on July 22, this may have resulted in runoff formation. Runoff is the carrier of sediment, but the energy of surface runoff might not be sufficient to move soil particles or may only be sufficient to transport pre-detached soil particles (Kinnell 2005; Alavinia et al. 2019). Moreover, soil surface features might delay sediment loss (Gómez and Nearing 2005).

Our results showed that the time taken to achieve peak runoff and sediment yield rates lagged behind peak rainfall intensity during the initial rainfall of the two intermittent rainfall events. This time-lag might have been due to low antecedent soil moisture content, or high rainfall intensity...
forming a temporary and relatively impermeable layer (Liu et al. 2002; Wang et al. 2018). However, the time taken to reach peak runoff rate was equal to, or earlier than the time of peak rainfall intensity during subsequent rainfalls within the two intermittent rainfall events. This may be explained by antecedent rainfall having moistened the soil, and soil infiltration gradually having become saturated with increasing rainfall intensity, thus the time to peak runoff rate gradually peaked earlier (Liu et al. 2011).

**Rill morphological characteristics**

Our results showed that the three rill types formed on bare soil were strip-shaped, V-shaped, and tree-branch-like.
networks. In agreement with our results, Rahma et al. (2017) showed that intermittent rills (strip-shaped) and multiple rills (tree-branch-like distribution) formed in sand and clay covered by straw. In our study, intermittent strip-shaped rills merged to form V-shaped rills due to runoff convergence; subsequently, continuous rills with a tree-branch-like distribution were formed by runoff convergence and headward erosion. Moreover, rills were mainly found to have widths in the range of 5–20 cm, and depths in the range of 0–10 cm after multiple natural rainfall events (rainfall amounts over 2 days ranged from 95 to 215.8 mm). This result is consistent with Guo et al. (2019), who reported rills with widths of 5–20 cm, and depths of 0–10 cm, following extreme rainfall (200 mm) on sloping farmland.

The mean rill length, width, and depth within bare soil all increased during our four subsequent rill observations. The mean rill length was the main indicator of soil erosion intensity on the slope surface. Variations in rill length 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 aggravating rill erosion (Cerdan et al. 2010). The connection of multiple intermittent rills (strip-shaped or V-shaped) in the same concentrated flow path to form a continuous rill may lead to a rapid increase of rill length (Zhang et al. 2017). Rill width–depth ratios ranged from 1.73 to 2.78 (Table 5), which shows that the side-wall collapse rate of rills was higher than the downcutting erosion of rills (Guo et al. 2019). This range of

| Table 5 | Changes in rill parameters on bare soil over our five rill observation times |
|----------------------------------|------------------|------------------|------------------|------------------|------------------|
| Rill indicators | Initial | 1st | 2nd | 3rd | 4th |
| $L_{\text{total}}$ (m) | 44.17 | 74.65 | 81.61 | 74.20 | 82.59 |
| $l_{\text{mean}}$ (m) | 6.31 | 14.93 | 20.40 | 14.84 | 20.65 |
| $l_{\text{range}}$ (m) | 1.45–16.70 | 1.45–44.06 | 1.45–50.56 | 1.45–45.77 | 1.45–51.57 |
| $W_{\text{mean}}$ (cm) | 11.53 | 10.06 | 12.81 | 13.42 | 14.51 |
| $W_{\text{range}}$ (cm) | 7.00–16.67 | 7.50–12.00 | 11.27–14.48 | 11.50–16.25 | 11.00–18.25 |
| $h_{\text{mean}}$ (cm) | 4.47 | 5.53 | 4.61 | 4.32 | 4.73 |
| $h_{\text{range}}$ (cm) | 3.15–5.75 | 4.10–9.00 | 3.45–5.13 | 3.25–4.75 | 4.35–5.23 |
| $\rho$ (m·m$^{-2}$) | 0.44 | 0.75 | 0.82 | 0.74 | 0.83 |
| $W/h$ | 2.78 | 1.98 | 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 |
| Belt of no erosion (m) | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 |

$L_{\text{total}}$ is the total length of rill; $L_{\text{mean}}$, $W_{\text{mean}}$, and $h_{\text{mean}}$ are the mean values of rill length, rill width, and rill depth, respectively; $l_{\text{range}}$, $W_{\text{range}}$, and $h_{\text{range}}$ are the ranges of rill length, rill width, and rill depth, respectively; rill density $= \rho$; rill width–depth ratio $= W/h$; convergence node $= c$; bifurcation node $= b$

| Table 6 | Rill number, density, and width–depth ratio of different slope sections over the five rill observation times |
|----------------------------------|------------------|------------------|------------------|------------------|------------------|
| Rill observations | Rill number | Rill density (m·m$^{-2}$) | Rill width–depth ratio |
|----------------------------------|------------------|------------------|------------------|
| I | II | III | I | II | III | I | II | III |
| Initial | 5 | 5 | 2 | 0.77 | 0.41 | 0.14 | 3.72 | 2.79 | 1.55 |
| 1st | 4 | 5 | 3 | 0.90 | 0.87 | 0.48 | 3.36 | 1.97 | 1.75 |
| 2nd | 4 | 5 | 2 | 0.90 | 0.89 | 0.66 | 2.96 | 1.98 | 2.19 |
| 3rd | 5 | 5 | 3 | 0.82 | 0.87 | 0.54 | 3.05 | 2.05 | 2.49 |
| 4th | 4 | 5 | 2 | 0.90 | 0.89 | 0.69 | 2.76 | 2.60 | 0.88 |

Fig. 6 Changes in rill width (a) and depth (b) with unit slope length for the five rill observation times
rill width–depth ratio is similar to that reported by Ran et al. (2018) in soils with high clay content.

Usually, rill development is preceded by a belt of no erosion, and the area required for rill initiation is 5–10 m (Torri et al. 1999). In our study, the belt of no erosion was 0.75 m after our four subsequent rill observations; this might be because of the lack of vegetation protection on the bare soil slope surface exposed to natural rainfall events. A similar result was reported by Rejman and Brodowski (2005), who found that the lack of a defined belt of no erosion could be connected to the location of the plots in the middle part of a loess soil slope during a storm event.

**Rill parameters of different bare soil slope sections**

The upper slope (section I) was smooth and without vegetation protection; it experienced relatively uniform flow and a weak runoff erosive force, and rills were densely and evenly distributed on the slope surface. Side-wall collapse erosion was mostly greater than downcutting erosion in all slope sections. Rill width and depth showed greater variability in the middle slope (section II) than in other sections, which indicates that the middle slope was the most active area of rill erosion development. This is similar to the work of Wu et al. (2018b), who reported that the maximum amount of local rill erosion occurred on the middle of the slope. This result can mainly be attributed to the variation in rill number (Table 6) and rill flow erosivity along the slope surface. Rill depth reached a minimum value on the lower slope (section III). This result is in accordance with Quan et al. (2020), who found that the main deposition areas of two different soil types were confined to the bottom of the plots. The reason behind this might be that runoff and sediment convergence from the upper slope to the lower slope decreased runoff transport capacity, thus increasing sediment silting on the lower slope. Moreover, the mean rill depth decrease might be due to the presence of depressions in the top surface of the lower slope (Gessesse et al. 2015); thus, the lower slope (section III) was the sediment deposition area.

In our study, the occurrence and development of rills were not observed using new technology or precise indicators. Thus, future studies should attempt to use three-dimensional photoreconstruction technique and micro-topography measurement technique, and observe hydraulic parameters in addition to morphological indicators to evaluate rill erosion processes (Di Stefano et al. 2017; Ou et al. 2021).

**Conclusions**

This study evaluated runoff, sediment transport processes, and the morphological characteristics of rills on bare, sloping farmland during multiple natural rainfall events. The peak runoff and sediment yield rates demonstrated a time-lag phenomenon compared with instantaneous rainfall intensity during both continuous and intermittent natural rainfall events. In the two intermittent rainfall events, the time at which the runoff and sediment yield rates peaked was later than the time of maximum rainfall intensity during the initial rainfall. However, it at the same time as the maximum rainfall intensity, or earlier, during subsequent rainfalls. Rills mainly had widths of 5–20 cm and depths of 0–10 cm. Rill erosion development was mainly reflected by an increase in mean rill length. The mid-slope (section II; 6.67–13.34 m) was the main active area of rill development, and the lower slope (section III; 13.34–20 m) was the sediment deposition area. This study provides essential information for the management of sloping farmland and provides a basis for future studies on rill erosion.

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

**Declarations**

**Ethics approval and consent to participate** Not applicable.

**Consent for publication** The studied participant consent for publication.

**Conflict of interest** The authors declare that they have no competing interests.

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