Inflow Rate Impact on Hillslope Erosion Processes and Flow Hydrodynamics

Inflow water from upslope is an extremely important factor that influences downslope erosion processes. Little information is available concerning how inflow water affects downslope erosion processes in the Chinese Mollisol region, where a large amount of runoff is generated from upslope. The purpose of this study was to determine the effects of inflow rate on erosion processes and flow hydrodynamic parameters. A soil pan (10 m long, 1.5 m wide, and 0.5 m deep) was subjected to rainfall simulation and inflow experiments under one rainfall intensity (50 mm h\(^{-1}\)), two slope gradients (5 and 10\(^{\circ}\)), and five inflow rates (50, 100, 150, 200, and 300 L min\(^{-1}\)). The result showed that when upslope inflow was included, soil loss increased 12 to 1950 times compared with no upslope inflow. When rill erosion dominated, rill erosion accounted for 52 to 90% of the total soil loss as the inflow rate increased from 50 to 300 L min\(^{-1}\). An increase in the inflow rate from 50 to 300 L min\(^{-1}\) caused the flow velocity to increase 0.6 to 7.8 and 1.7 to 12.9 times at 5 and 10\(^{\circ}\) slopes, respectively, while the Darcy–Weisbach coefficient decreased from 13.5 to 95.4%. For sheet-dominated erosion, significant linear regressions were fitted between shear stress, stream power, unit stream power, and inflow rate; but for rill-dominated erosion, power functions were established between these flow hydrodynamic parameters and the inflow rate.

Oil erosion during rainfall is a complex phenomenon, including soil detachment by raindrop impact and surface flow, soil particle transportation by raindrop splash and surface flow, and sediment deposition (Ellison, 1947). On the basis of Ellison’s work, Meyer and Monke (1965) proposed that runoff is one of the main erosive agents in water erosion processes. Flow detachment and transport capacity were strongly related to concentrated flow in a bare fallow field (Guo et al., 2013; Schiettecatte et al., 2008). Zhang et al. (2009) demonstrated that sediment transport capacity increased as a power function with runoff rate on a steep landscape. Additionally, inflow water from upslope had a great impact on downslope erosion processes and caused rill flow to shift from laminar flow to turbulent flow (Al-Hamdan et al., 2012; Chen, 1992; Xiao et al., 2005; Zhang et al., 2015; Zheng et al., 2000, 2004).

A landscape with a gentle slope and a long slope length is one of the basic geographic characteristics of the Chinese Mollisol region (Zhang et al., 2006), which induces a large amount of runoff from upslope. There is little information, however, related to impacts of the inflow water from upslope on downslope erosion processes in the Chinese Mollisol region. Moreover, designed inflow rates in previous studies were mostly below 60 L min\(^{-1}\) (Al-Hamdan et al., 2012; Giménez and Govers, 2002; Nearing et al., 1997; Proffitt et al., 1991), which is far below the actual inflow rate from upslope under the field conditions of the Chinese Mollisol region. Runoff from upslope in the Chinese Mollisol region not only could have great impacts on downslope soil erosion rates but also could change the dominant erosion process so that it shifts from sheet erosion to rill and ephemeral gully erosion. Therefore, it is necessary to quantify the effects of the inflow rate on
downslope erosion processes on the long, gentle landscape in the Chinese Mollisol region to protect valuable soil resources.

Overland flow on hillslopes frequently occurs as a mixture of broad sheet flow, which is found in interrill areas, and concentrated flow, which occurs within rills (Gilley et al., 1990). Once the slope erosion pattern evolves from splash and sheet erosion patterns to a rill erosion pattern, the rate and magnitude of soil erosion is significantly enhanced and interrill erosion accounts for only a very small percentage of the overall erosion amount (Auerswald et al., 2009; He et al., 2014; Shen et al., 2016). This is due to the fact that rill formation could enhance both the hydraulic erosion force and sediment transport ability by converging and capturing most runoff on the slope. The controlling variables, which involve inflow rate, flow velocity, Reynolds number, Froude number, and Darcy–Weisbach coefficient, and combined indicators derived from former variables, like shear stress, stream power, and unit stream power (Gilley et al., 1990; Govers, 1992; Guo et al., 2013; Knapen et al., 2007; Zhang et al., 2003, 2009) have some relative advantages in depicting the dynamic processes of sheet erosion and rill erosion. For different erosion patterns, the effectiveness of the hydrodynamic parameters is different in describing hydrodynamic processes (Zhang et al., 2015). However, little research has focused on the inflow rate impacts on flow hydraulic or hydrodynamic parameters under different dominant erosion patterns (e.g., Peng et al., 2014; Schiettecatte et al., 2008; Wu et al., 2010). Thus, it is imperative to study the effects of the inflow rate on flow hydraulic and hydrodynamic parameters under different dominant erosion patterns.

Therefore, a laboratory study was conducted to quantify how the inflow rate affects hillslope erosion processes in the Chinese Mollisol region. The specific objectives were to quantify the effects of the inflow rate on hillslope soil erosion processes, to compare the impacts of the inflow rate on flow hydraulic and hydrodynamic parameters under different dominant erosion patterns, and to select the crucial parameters affecting sheet- and rill-dominant erosion patterns. The findings will help to elucidate soil erosion mechanisms on long, gentle slopes and provide an approach for controlling hillslope erosion in the Chinese Mollisol region.

### MATERIAL AND METHODS

#### Experimental Equipment and Materials

The experiments were conducted in the rainfall simulation laboratory of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Yangling City, China. A down sprinkler rainfall simulator system was used to apply rainfall (Zhou et al., 2000). The rainfall simulator, which includes three nozzles, can be set to any selected rainfall intensity ranging from 30 to 350 mm h\(^{-1}\) by adjusting the nozzle aperture size and water pressure; the fall height of raindrops is 18 m above the ground. The simulated raindrop diameter distribution was 0.2 to 3.1 mm, and >85% of raindrop diameters were <1.0 mm. The simulated storm had raindrop sizes and distribution similar to natural rainfall (Zhou et al., 2000).

A slope-adjustable soil pan was used in this study that is 10.0 m long, 1.5 m wide, and 0.5 m deep, with many drainage holes (2-cm aperture) at the bottom to facilitate water discharge. The slope gradient ranges from 0 to 30° with adjustment step of 5°. The inflow experiment equipment consisted of an overflow tank to produce inflow water, which was attached to the upper end of the soil pan, and a runoff collector to collect runoff samples, which was installed at the bottom of the soil pan. Additional details about the inflow experimental setup were provided by Wen et al. (2015).

The soil used in this study was collected from the 0- to 20-cm depth of a maize field (Zea mays L.) field in Liu Jiaji Town (44°43' N, 126°11' E), Yushu City, Jilin Province, in the center of the Chinese Mollisol region. The soil was classified as a Mollisol (US soil taxonomy) with 76.4% silt (0.05–0.002 mm), 20.3% clay (<0.002 mm), 3.3% sand (>0.05 mm) content, and 23.8 kg m\(^{-1}\) soil organic matter (potassium dichromate method).

#### Experimental Design

The slope gradient typically ranges from 1 to 5° in the Chinese Mollisol region (Fan et al., 2004). Cui et al. (2007) reported that when the slope gradient was >7°, soil erosion became more severe. Therefore, 5 and 10° were used in this study. According to the results of Zhang et al. (1992), the average momentary rainfall intensity that causes a moderate intensity of soil erosion is about 42.6 mm h\(^{-1}\). Therefore, 50 mm h\(^{-1}\) was used as the experimental rainfall intensity in this study. Inflow rates were designed according to the runoff rate collected from various slope lengths in field plots. The set of designed inflow rates (50, 100, 150, 200, and 300 L min\(^{-1}\)) were collected from slope lengths from 100 to 450 m when the maximum 10-min rainfall intensity was 75 mm h\(^{-1}\). For treatments when the inflow rate was 0, runoff and soil loss were induced only by a 50 mm h\(^{-1}\) rainfall intensity.

#### Soil Pan Preparation

The soil was air dried, and impurities such as organic matter and gravels were removed. To maintain its natural state, the soil was not passed through a sieve to preserve its original aggregation (Huang, 1998). Before packing the soil pan, the water content of the soil was determined and used to calculate how much soil was needed to pack the soil pan for different soil layers. First of all, a 10-cm sand layer was packed at the bottom of the soil pan to allow free drainage of excessive water. Then a 15-cm-depth sticky loess layer to simulate the plow layer was packed on top of the sand layer at a mean bulk density of 1.30 g cm\(^{-3}\). A 20-cm Mollisol layer was packed into the soil pan in 5-cm increments on top of the loess layer at a mean bulk density of 1.15 g cm\(^{-3}\) to simulate the plow layer.

#### Experimental Procedures

Once the soil pan was prepared, a pre-wetting rain was conducted at an intensity of 30 mm h\(^{-1}\) and stopped after surface flow occurred, usually after about 40 min. One day after the pre-wetting rain and before running the experiments, calibrations of the rainfall intensity and inflow rate were conducted to reach the experimental requirements. The soil pan was then adjusted to
the 50 mm h⁻¹ rainfall intensity and subjected to the designed slope gradient (5 or 10°) and inflow rate (0, 50, 100, 150, 200 or 300 L min⁻¹). For the experiments, only simulated rainfall was applied at first period (lasting about 30 min), and the inflow experiments started when runoff rates under the rainfall simulation were stabilized. A total of 12 treatments were tested. Each of the inflow rates lasted 10 min, and the total experimental treatment lasted about 40 min. Two replicates were conducted for each experimental variation.

**Measurements of Runoff, Soil Loss, Flow Velocity, and Rill Development**

For each treatment, runoff samples were collected by either 15- or 60-L buckets at 1-min intervals as soon as runoff occurred. These samples were weighed, and the suspended sediment was allowed to settle out. The clear supernatant was decanted and the remaining sediment was oven dried at 105°C for 24 h to determine the soil loss and calculate the sediment concentration.

Surface flow velocity was measured at five slope sections (1, 3, 5, 7, and 9 m) at 3-min intervals using the dye tracing method with 0.8% (w/w) KMnO₄. The time at which the tracer reached the marked distance (0.5 m) was determined by the color-front propagation. The flow depth and width were measured by a steel ruler (0.1-mm precision) after rills were generated. After each run, rill width and depth measurements were conducted along each rill at intervals of 5 or 10 cm. Furthermore, these measurements were also performed when sudden changes in the flow hydrodynamic parameters.

Manual measurements of each rill’s width, depth, and location (x, y) along with rainfall duration were performed using a steel ruler (0.1-mm precision) after rills were generated. After each run, rill width and depth measurements were conducted along each rill at intervals of 5 or 10 cm. Furthermore, these measurements were also performed when sudden changes in the rill pattern occurred (Øygarden, 2003). The measurements were used to calculate rill volumes and estimate the magnitude of rill erosion (Shen et al., 2016).

**Data Analysis and Statistical Analysis**

The surface flow velocity was used to estimate the mean flow velocity as

\[ v = kv_m \]  

where \( v_m \) (m s⁻¹) is the surface flow velocity measured and calculated using the dye method, \( v \) is the mean flow velocity (m s⁻¹), and \( k \) is a coefficient taken to be 0.75 (Xiao et al., 2011).

The flow depth under a sheet erosion pattern was calculated as (Zhang et al., 2015)

\[ b = \frac{Q}{\nu B t} \]  

where \( b \) (m) is the flow depth, \( Q \) (m³) is the runoff amount during a period of time \( t \) (s), and \( B \) (m) is the width of the surface flow.

The Darcy–Weisbach coefficient can be calculated as (Abrahams et al., 1986)

\[ f = \frac{8gRJ}{v^2} \]  

where \( f \) is the Darcy–Weisbach coefficient, \( J \) (m m⁻¹) is the surface slope, \( g \) is the acceleration due to gravity (9.80 m s⁻²), and \( R \) (m) is the hydraulic radius.

Flow shear stress is an important factor for runoff energies to deliver the mass in runoff and was calculated as (Nearing et al., 1991)

\[ \tau = \gamma RJ \]  

where \( \tau \) (Pa) is the flow shear stress and \( \gamma \) (kg m⁻³) is the mass density of the water–sediment mixture.

Stream power is defined as the power of water per unit area, which reflects the sediment transport capacity of runoff, and was calculated as (Nearing et al., 1991)

\[ \omega = \tau \nu \]  

where \( \omega \) (N m⁻¹ s⁻¹) is the stream power.

The unit stream power was calculated as (Moore and Burch, 1986)

\[ \varphi = \nu J \]  

where \( \varphi \) (m s⁻¹) is the unit stream power.

All analyses were performed using SPSS Version 19.0 (SPSS Inc.). Analysis of variance (ANOVA) was conducted to examine significant differences in runoff rates, soil loss rates, sediment concentrations, flow depths, and rill erosion among the different inflow rates. A correlation matrix of the Pearson correlation coefficients was used to analyze the correlations between soil loss and flow hydrodynamic parameters.

**RESULTS AND DISCUSSION**

**Inflow Rate Impact on Hillslope Runoff**

When there was no inflow water, the stable runoff rate didn’t have obvious differences between the 5 and 10° slopes in this study (Table 1). For treatments with inflow water, there were significant differences among the five inflow rates for the 5 and 10° slopes. Runoff rates increased with the increase of inflow rate (Table 1). Whether the slope gradient changed from 5 to 10° or the dominant erosion pattern shifted from sheet erosion to rill erosion, the runoff rate was approximately equal to the runoff rate induced by rainfall plus the designed inflow rate.

**Inflow Rate Impact on Hillslope Soil Loss**

The soil loss trends were greatly different from the runoff rate trends (Table 1). For treatments without inflow water, because only sheet erosion occurred (Fig. 1a), soil loss was lower, shifting from 0.4 to 0.7 g min⁻¹ m⁻² when the slope gradient changed from 5 to 10°. For treatments with inflow water, soil loss was significantly different from those without inflow water. Compared with treatments without inflow water, at a 5° slope where sheet erosion was dominant, soil loss increased 12.5 to 19.8 times as the inflow rate increased from 50 to 300 L min⁻¹, while at a 10° slope where rill erosion was dominant, soil loss increased 30.1 to 1950.4 times. The results indicated that inflow water from upslope greatly affected downslope erosion rates, and
the effects of the inflow rate on soil loss were influenced by the dominant erosion process.

For treatments with inflow water at a 5° slope (Fig. 1b), soil loss did not have significant differences among the 50, 100, and 150 L min⁻¹ inflow rates, but soil loss at 200 and 300 L min⁻¹ inflow rates was significantly different. Soil loss increased 42.6 and 53.7% at the 200 and 300 L min⁻¹ inflow rates, respectively, compared with that at the 50 L min⁻¹ inflow rate (Table 1). Because the flow depths (6.2–7.9 mm at 50–300 L min⁻¹ inflow rates compared with the other inflow rates. Probably induced the significant difference in soil loss at 200 and 300 L min⁻¹ inflow rates caused an increase in soil loss (Fig. 1c). This from 100 to 300 L min⁻¹, the sediment concentration showed among the different inflow rates when rill erosion

<table>
<thead>
<tr>
<th>Slope</th>
<th>Inflow rate</th>
<th>Runoff rate</th>
<th>Soil loss</th>
<th>Sediment concentration</th>
<th>Flow depth</th>
<th>Rill erosion</th>
<th>Proportion of soil loss</th>
<th>Dominant erosion pattern</th>
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<tbody>
<tr>
<td>5</td>
<td>0</td>
<td>9.5 (0.2) a</td>
<td>0.4 (0.1) a</td>
<td>0.6 (0.1) a</td>
<td>2.2 (0.1) a</td>
<td>–</td>
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<td>sheet erosion</td>
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<td></td>
<td>50</td>
<td>57.4 (7.9) b</td>
<td>5.4 (0.1) b</td>
<td>1.6 (0.1) b</td>
<td>6.2 (0.2) b</td>
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<td></td>
<td>100</td>
<td>113.4 (7.1) c</td>
<td>5.2 (0.3) b</td>
<td>0.7 (0.0) a</td>
<td>6.2 (0.1) b</td>
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<td></td>
<td>150</td>
<td>151.1 (12.9) d</td>
<td>5.1 (0.4) b</td>
<td>0.5 (0.0) a</td>
<td>7.0 (0.4) c</td>
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<tr>
<td></td>
<td>200</td>
<td>216.9 (5.0) e</td>
<td>7.7 (0.4) c</td>
<td>0.5 (0.0) a</td>
<td>6.6 (0.0) bc</td>
<td>–</td>
<td>–</td>
<td>sheet erosion</td>
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<tr>
<td></td>
<td>300</td>
<td>298.6 (6.8) f</td>
<td>8.3 (0.4) c</td>
<td>0.5 (0.1) a</td>
<td>7.9 (0.1) d</td>
<td>–</td>
<td>–</td>
<td>+ rill head cut</td>
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<tr>
<td></td>
<td>0</td>
<td>9.3 (0.1) a</td>
<td>0.7 (0.1) a</td>
<td>1.1 (0.0) a</td>
<td>2.0 (0.1) a</td>
<td>–</td>
<td>–</td>
<td>sheet erosion</td>
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<tr>
<td>10</td>
<td>50</td>
<td>62.6 (8.8) b</td>
<td>21.8 (2.1) b</td>
<td>5.8 (0.3) b</td>
<td>12.1 (0.4) b</td>
<td>11.4 (0.8) a</td>
<td>52.3</td>
<td>rill erosion</td>
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<tr>
<td></td>
<td>100</td>
<td>107.3 (3.7) c</td>
<td>156.0 (9.7) c</td>
<td>21.3 (1.1) c</td>
<td>39.3 (0.8) c</td>
<td>98.2 (12.3) b</td>
<td>63.0</td>
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<td></td>
<td>150</td>
<td>161.4 (5.6) d</td>
<td>566.5 (11.6) d</td>
<td>52.6 (2.5) d</td>
<td>48.2 (0.5) d</td>
<td>420.1 (16.2) c</td>
<td>74.2</td>
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<tr>
<td></td>
<td>200</td>
<td>219.0 (17.1) e</td>
<td>1366.0 (33.5) f</td>
<td>101.0 (9.0) f</td>
<td>70.6 (0.9) f</td>
<td>1224.4 (42.6) e</td>
<td>89.6</td>
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<td></td>
<td>300</td>
<td>309.1 (39.1) f</td>
<td>11085.5 (31.2) e</td>
<td>53.8 (6.3) e</td>
<td>58.9 (0.8) e</td>
<td>878.8 (57.8) d</td>
<td>79.3</td>
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</tbody>
</table>

† Standard deviation in parentheses. Mean values for different inflow rates with the same slope gradient followed by different letters are significantly different at p < 0.05 according to the Tukey test.

There were obvious differences in the trends in sediment concentration among the different inflow rates when rill erosion dominated (Table 1). The sediment concentration increased with the increase in runoff rate at 50 to 200 L min⁻¹ inflow rates, but the sediment concentration at the 300 L min⁻¹ inflow rate was only 53.3% of that at 200 L min⁻¹. The increasing sediment concentration from 50 to 200 L min⁻¹ inflow rates implies that the dominant sediment regime might be transport limited. There were two reasons for the sharp decline of sediment concentration at the 300 L min⁻¹ inflow rate: (i) a large amount of sediment was deposited downslope at the 300 L min⁻¹ inflow rate, while little sediment deposition was found at 200 L min⁻¹; and (ii) the rill morphology at the 300 L min⁻¹ inflow rate was quite different from that at the 200 L min⁻¹ inflow rate, which also might influence flow sediment transport and deposition processes.

Contribution of Rill Erosion

As mentioned above, soil loss dramatically increased with the initiation and development of rills. The trend of rill erosion was similar to that of soil loss at the 50 to 300 L min⁻¹ inflow rates (Table 1). There were significant differences in the amount of rill erosion among the five inflow rates under a predominantly rill erosion pattern. The rill erosion amount increased 7.6, 35.9, 106.4, and 76.1 times at the 100, 150, 200, and 300 L min⁻¹ inflow rates, respectively, compared with that at the 50 L min⁻¹ inflow rate (Table 1). The reason was that rill flow erosivity increased with the increasing inflow rate. The contributions of rill erosion to soil loss were quite high, especially at the larger inflow rates (150–300 L min⁻¹) (Table 1). Inflow water concentrates
into rill channels and then triggers an increase in the rill development speed and rill flow transport capacity, which consequently lead to greater rill erosion at larger inflow rates (Wells et al., 2009).

Generally, rill length, mean width, and depth all increased with the increasing inflow rate from 50 to 200 L min⁻¹ (Fig. 2). Rill lengths at the 200 L min⁻¹ inflow rate were 25.0, 4.7, and 1.7 times larger than those at 50, 100, and 150 L min⁻¹, respectively. According to experimental observations, there were only discontinuous and shallow micro-rills distributed on the hillslope at the 50 to 150 L min⁻¹ inflow rates, but a long continuous rill formed from upslope to downslope at the 200 L min⁻¹ (Fig. 1d), which could provide a channel for concentrated flow, leading to a mass of soil loss. Rill erosion at the 300 L min⁻¹ inflow rate accounted for only 47.1% of that at the 200 L min⁻¹ inflow rate (Table 1). Rills occurred earlier and faster at the 200 L min⁻¹ inflow rate than at the 300 L min⁻¹ rate. A continuous rill was formed at the 200 L min⁻¹ inflow rate, which could provide a rill channel for concentration of upslope runoff (Fig. 1d). However, for the 300 L min⁻¹ inflow rate, rills developed fast at an early stage of the experiment, rill depths upslope were much larger than those downslope, and plenty of loose material was transported by the concentrated flow upslope. Within a certain slope length, the energy of flow was enough for sediment transport. Beyond this slope length, sediment deposition might occur in the downslope section (Lei and Nearing, 2000). Once deposition occurred, the materials would block the rill channel and caused a reduction of the flow velocity due to decentralized runoff (Fig. 1c). The deposition of sediment caused the mean rill width become wider and the mean rill depth to become shallower at the 300 L min⁻¹ inflow rate than at the 200 L min⁻¹ inflow rate.

As seen in Fig. 1c, some of the sediment load was deposited downslope at the 300 L min⁻¹ inflow rate. This result agrees with the results of Zhang et al. (2006), who pointed out that many eroded soil materials associated with runoff were redeposited on low-lying land. By using magnetic susceptibility measurements to quantify soil redistribution in the Northeast region of China, Liu et al. (2015) indicated that the maximum soil deposition (25.1%) was observed at the footslope. This result could help to understand the unique soil erosion characteristics in the Chinese Mollisol region, where soil loss on hillslopes is severe, while river sediment delivery is relatively low (Fan et al., 2004).

**Inflow Rate Impact on Flow Hydrodynamic Parameters**

Hillslope erosion was greatly influenced by flow hydraulic properties and flow resistance conditions (Peng et al., 2014; Zhang et al., 2009). Flow velocity is one of the key factors that influences flow detachment and transport processes on hillslopes (Mancilla et al., 2005). The Darcy–Weisbach coefficient, one of the most often used parameters, can present the resistance of slope surface conditions to runoff (Reichert and Norton, 2013). Shear stress, stream power, and unit stream power are three basic hydrodynamic parameters for evaluating the dynamic mechanisms of soil erosion (Ali et al., 2012; Nearing and Parker, 1994; Nearing et al., 1999). Therefore, flow velocity, the Darcy–Weisbach coefficient, shear stress, stream power, and unit stream power were selected to evaluate the effects of the inflow rate on soil erosion processes.

When there was no inflow water, the mean flow velocities were only 4.9 and 5.1 cm s⁻¹ for 5 and 10° slopes, respectively.
For treatments with inflow water, mean flow velocities increased 0.6 to 7.8 and 1.7 to 12.9 times compared with those without inflow water at the 5° slope where sheet erosion dominated and the 10° slope where rill erosion dominated, respectively, as the inflow rate ranged from 50 to 300 L min⁻¹ (Fig. 3a). The results show that inflow water from upslope had a significant impact on the flow velocity, and inflow water effects on the flow velocity were dependent on the dominant erosion pattern. For predominantly rill erosion at the 10° slope, mean flow velocities increased 39.3 to 113.3% compared with those when sheet erosion predominated as the inflow rate increased from 50 to 300 L min⁻¹. These increments also indicate the obviously positive impact of rill initiation and development on the flow velocity.

Power functions were fitted between mean flow velocities and inflow rates for both sheet and rill erosion dominant processes (Fig. 3a). The results were consistent with the conclusions of Nearing et al. (1999) and Zhang et al. (2002). By using data under both inflow and rainfall simulation experiments, Schiettecatte et al. (2008) found a power function between flow velocity (m s⁻¹) and flow discharge (Q, m³ s⁻¹): \( v = 10Q^{0.44} \).

The value of the power exponent in Schiettecatte’s equation, 0.44, was lower than those in this study, 0.88 and 0.76 for sheet and rill dominant erosion patterns, respectively. This indicates that the increase in the magnitude of flow velocity in this study was greater than that in Schiettecatte’s study. The reason might be that the inflow rate in Schiettecatte’s study was lower than 30 L min⁻¹, while in this study the inflow rate was greater than 50 L min⁻¹. Govers (1992) also established a power function between flow velocity and inflow rate under rill erosion, with a power function exponent of only 0.29, which is much lower than the 0.76 in this study. The probable reasons are the differences in the range of experimental inflow rates and soil erodibility.

When there was no inflow water, the Darcy–Weisbach coefficient values were much higher than those treatments with inflow water. For treatments with inflow water, the average \( f \) values decreased from 13.5 to 95.4% when the inflow rate increased from 50 to 300 L min⁻¹ compared with the treatments without inflow water. The average \( f \) values declined more sharply with the increasing inflow rate under sheet erosion than rill erosion (Fig. 3b). Zheng et al. (2004) pointed out that upslope runoff caused a decrease in
the rill flow resistance coefficient in their studies, and the same relationship was also found by Zhang et al. (2002). However, the average $f$ values were higher for the case of sheet erosion domination than rill erosion domination at 50 and 100 L min$^{-1}$ inflow rates (Fig. 3b). The reason was that the increase in flow depth could reduce the surface resistance of the hillslope under the sheet erosion domination pattern (Zhang et al., 2015). When inflow rates were >100 L min$^{-1}$, the average $f$ values of the sheet dominant erosion pattern were lower than those under the rill dominant erosion pattern. Nearing et al. (1997) pointed out that rill morphology has a great influence on the rill flow resistance.

For treatments without inflow water, the shear stress, stream power, and unit stream power values were 1.88 and 3.40 Pa, 0.09 and 0.17 N m$^{-1}$ s$^{-1}$, and 0.004 and 0.009 m s$^{-1}$ for the 5 and 10$\degree$ slopes, respectively. For treatments with inflow water and dominated by sheet erosion, compared with the treatment without inflow water, the shear stress, stream power, and unit stream power values increased 1.7 to 2.7, 1.4 to 15.3, and 0.1 to 3.2 times, respectively, as the inflow rate increased from 50 to 300 L min$^{-1}$; while for rill erosion domination, the shear stress, stream power, and unit stream power values increased 1.7 to 14.9, 6.5 to 189.0, and 1.7 to 12.9 times, respectively (Fig. 4). The relationships of shear stress, stream power, and unit stream power with the inflow rate were different between predominantly sheet erosion and predominantly rill erosion. For predominantly sheet erosion, a significant linear relationship was fitted between shear stress, stream power, and unit stream power and the inflow rate. For predominantly rill erosion, shear stress, stream power, and unit stream power were related to the inflow rate to the 1.07th, 1.83th, and 0.76th power functions. This indicates that the existence of rills positively influenced the flow hydrodynamic parameters. It is necessary then to consider the effects of inflow water on the flow hydrodynamic parameters for different erosion patterns.

**Correlations between Soil Loss and Flow Hydrodynamic Parameters**

Flow velocity is directly related to soil loss, sediment transport, deposition, and rill formation and development. Mancilla et al. (2005) indicated that a higher flow velocity implied the formation of more rills. Zhang et al. (2009) found a linear function between

![Graph showing relationships between shear stress, stream power, and unit stream power and inflow rate.](image-url)

**Fig. 4.** Relationships between (a) shear stress, (b) stream power, and (c) unit stream power and the inflow rate under sheet and rill dominant erosion patterns.
mean flow velocity and measured sediment transport capacity. Nearing and Parker (1994) stated that the sediment detachment rate increased with the increase in shear stress on a hillslope. Zhang et al. (2009) reported that the sediment transport capacity had a very close regression with shear stress, stream power, or unit stream power. Ali et al. (2012) also proposed that stream power and unit stream power were greatly related to the flow transport capacity.

Pearson correlation analysis was used to determine the crucial hydrodynamic parameters affecting hillslope soil loss (Table 2). The results indicate that when sheet erosion was dominant, the crucial hydraulic and hydrodynamic parameters that affected soil loss were \( v, \omega, \) and \( \varphi, \) and the correlation coefficient between \( \omega \) and soil loss was the largest (Table 2). For the rill-dominant erosion pattern, the key hydraulic and hydrodynamic parameters that influenced soil loss were \( v, f, \tau, \omega, \) and \( \varphi, \) and \( v \) was the most highly correlated parameter with soil loss. Previous studies (Al-Hamdan et al., 2012; Cao et al., 2009) indicated that stream power performed better than other hydrodynamic parameters. Zhang et al. (2002) proposed that mean flow velocity had a better correlation with the detachment rate than other hydraulic parameters, and the detachment rate had a better power function correlation with stream power than shear stress or unit stream power. Additionally, Shen et al. (2016) also indicated that flow velocity was the most sensitive hydraulic parameter to estimate rill erosion.

In sum, the effects of flow hydrodynamic parameters on soil loss were significantly affected by the dominant erosion patterns. However, some previous studies rarely considered erosion pattern effects on hillslope soil loss when analyzing the relations between soil loss and flow hydrodynamic parameters. In this study, when the inflow water was large enough to eliminate the disturbance effects of raindrops, the shear stress on sheet-dominant erosion had less impact on soil erosion. Zhang et al. (2002) also concluded that soil detachment by shallow flow had a better correlation with flow energy than shear stress.

**CONCLUSIONS**

In this study, simulated rainfall and inflow experiments focusing on the effects of the inflow rate (50–300 L min\(^{-1}\)) on hillslope soil erosion processes were conducted. The results showed that the effects of inflow water on hillslope soil loss were dependent on the dominant erosion pattern. Compared with treatments without inflow water, soil loss increased 12 to 20 times when the inflow rate ranged from 50 to 300 L min\(^{-1}\) at 5° slope where sheet erosion was dominant, while soil loss increased 30 to 1950 times as the inflow rate increased from 50 to 300 L min\(^{-1}\) at 10° slope where rill erosion was dominant. Compared with dominant sheet erosion, soil loss under predominantly rill erosion increased 3.0, 29.0, 110.1, 176.4, and 132.6 times as the inflow rate increased from 50 to 300 L min\(^{-1}\). Once rills formed on the hillslope, the contributions of rill erosion to hillslope soil loss were >63%.

Values of \( v, \tau, \omega, \) and \( \varphi \) for treatments with inflow water were larger than those without inflow water, while the \( f \) values showed an opposite trend. For treatments with inflow water, mean flow velocity expressed a power function with inflow rate for both sheet and rill erosion patterns. The \( f \) values decreased more sharply with an increase of the inflow rate for sheet erosion than rill erosion. The values of \( \tau, \omega, \) and \( \varphi \) expressed a linear function with inflow rate for the predominantly sheet erosion pattern, while power functions were found between \( \tau, \omega, \) as well as \( \varphi \) and the inflow rate for the rill erosion pattern. Pearson correlation analysis results indicated that the crucial hydrodynamic parameters that affected soil loss were \( \omega, v, \) and \( \varphi \) when sheet erosion predominated and \( v, \varphi, \omega, \tau, \) and \( f \) when rill erosion predominated. The shear stress under sheet erosion had less impact on soil erosion when the inflow water was large enough to eliminate the disturbance effects of raindrops. Therefore, some practices should be implemented to disperse runoff from upslope on the long, gentle slopes and prevent the occurrence of rills on hillslopes in the Chinese Mollisol region.

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**REFERENCES**


**Table 2. Correlation matrix between soil loss and flow hydrodynamic parameters of soil loss (SL), flow velocity (\( v \)), Darcy–Weisbach coefficient (\( f \)), flow shear stress (\( \tau \)), stream power (\( \omega \)), and unit stream power (\( \varphi \)) under dominantly sheet or rill erosion.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SL</th>
<th>( v ) ( 1.000 )</th>
<th>( f )</th>
<th>( \tau )</th>
<th>( \omega )</th>
<th>( \varphi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL</td>
<td>1.000</td>
<td>0.817** 1.000</td>
<td>-0.463</td>
<td>-0.766** 1.000</td>
<td>0.236 0.182 0.347 1.000</td>
<td>0.836** 0.987** -0.693* 0.309 1.000</td>
</tr>
<tr>
<td>Sheet erosion (n = 10)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SL</td>
<td>1.000</td>
<td>0.967** 1.000</td>
<td>-0.685* -0.781** 1.000</td>
<td>0.892** 0.915** -0.615 1.000</td>
<td>0.961** 0.955** -0.637* 0.969** 1.000</td>
<td>0.966** 1.000** -0.783** 0.915** 0.955** 1.000</td>
</tr>
<tr>
<td>Rill erosion (n = 10)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

* Significant at \( p < 0.05 \).
** Significant at \( p < 0.01 \).


