

# Effects of flow hydraulics on total nitrogen loss on steep slopes under simulated rainfall conditions

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## ABSTRACT

Flow hydraulics play important roles in soil erosion and loss of soil nutrients. A better understanding of the relationship between flow hydraulics and nutrient losses will improve chemical transport modeling. The laboratory experiment was conducted to determine flow hydraulics' effects on total nitrogen (TN) loss. The impacts of rainfall intensities (0.6, 1.1, 1.61, 2.12, and 2.54 mm·min<sup>-1</sup>) and slope gradients (10°, 15°, and 20°) on TN loss were also studied. Selected soils were derived from purple sandy shales, which are the main parent materials in Wangjiaqiao watershed, southern China. Results show that negative linear relationships ( $R^2 = 0.71$ ) were observed between the rate of Manning roughness coefficient to average flow depth and the unit area runoff-associated TN transport rate. There was a good linear relationship between the unit area sediment-associated TN transport rate and Reynolds numbers ( $R^2 = 0.90$ ), flow velocity ( $R^2 = 0.87$ ), and stream power ( $R^2 = 0.73$ ), while Froude numbers, Darcy–Weisbach and Manning friction coefficients were not good hydraulic indicators of the sediment-associated TN loss of purple soil. The equation including stream power and flow velocity may have a better correlation coefficient ( $R^2 = 0.94$ ).

**Key words** | flow hydraulics, nitrogen losses, purple soil, runoff, sloping cropland

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## INTRODUCTION

Soil erosion and loss of soil nutrients has become a global environmental problem of growing concern. Physically, nutrients can move from soil to water as they become dissolved in runoff water or may be moved in particulate form when bound to suspend sediment (Panuska *et al.* 2008). The loss of soil nutrients depends on soil conditions, rainfall intensity, flow hydraulic, slope, and vegetation cover (Fraser *et al.* 1999; Pan & Shangguan 2006). Understanding how nutrients are transported from hillslope to water and their dynamic can also provide an important basis for ecological restoration.

Soil nutrient from the sloping cropland to the stream is controlled by the interaction of nutrient source factors (soil, crop, and land use) with its transport factors (surface runoff, subsurface runoff (SSR), and sediment). Zöbisch *et al.* (1995)

reported that total loss of nutrients was dependent on the total amount of runoff and soil loss. Researches indicate that both surface and SSR are important hydraulic pathways for nutrient transport (Jia *et al.* 2007). The generation of SSR depends on soil properties, water conductivity, slope gradient, and rainfall intensity (Naef *et al.* 2002). The hydrological processes and the associated erosional responses are known to be related to soil properties. Many reasons, such as shallow and loose soil layer, the excessive use of nitrogen, and numerous rainstorms, have caused serious soil erosion in the purple soil region, and is a major environmental problem in China (Fu *et al.* 2011; Peng *et al.* 2014). Average soil erosion rates in the purple soil region have reached 3,400 t km<sup>-2</sup> year<sup>-1</sup>, and in some areas even reached 9,000 t km<sup>-2</sup> year<sup>-1</sup> (Wen *et al.* 2005).

Considering purple soil showing the overlying soil and underlying rock which is known as ‘the Geotechnical dual structure’, SSR is a prominent runoff process in purple soil slope (Niu *et al.* 2010). Hubbard & Sheridan (1983) reported that from a small, upland, coastal plain watershed, 99% of total NO<sub>3</sub>-N loss occurred in SSR. Moreover, a vast number of studies have investigated relationships that describe sediment detachment and nutrient transport. The general agreement is that suspended sediment serves as the delivery mechanism for nutrient pollutants (Shi *et al.* 2012; Molder *et al.* 2015). The amount of nutrient loss is directly proportional to the amount of soil loss (Kothyari *et al.* 2004). More information on slope hydrological processes and nutrient transformation of purple soil is needed to better understand the behavior and interaction of the different pathways from runoff and sediments that make up nutrients’ transport processes.

As soil erosion by rainfall is highly dependent on flow hydraulic properties (flow velocity, flow regime, stream power, and hydraulic resistance), often, concepts were taken from the literature on alluvial rivers and applied to slope erosion. Flow velocity ( $V$ ) can be used to study rill erosion according to the self-similarity theory (Di Stefano *et al.* 2013). Sajjadi & Mahmoodabadi (2015) indicated that rain-induced sediment concentration at small scales can be modeled on the basis of flow velocity. Reynolds number ( $Re$ ) is an important parameter to describe the hydraulic characteristics of the rill flow:

$$Re = \frac{Vh}{\nu} \quad (1)$$

where  $h$  is mean flow depth (m),  $V$  is flow velocity (m·s<sup>-1</sup>),  $\nu$  is kinematic viscosity coefficient (m<sup>2</sup>·s<sup>-1</sup>). For a given shear stress, detachment rate by shallow flow is primarily associated with flow regime (Nearing & Parker 1994). Many studies have incorporated stream flow equations and variables to characterize hydraulic resistance, expressed as Darcy–Weisbach ( $f$ ) and Manning friction coefficients ( $n$ ):

$$f = \frac{8ghS}{V^2} \quad (2)$$

$$n = V^{-1}S^{1/2}h^{2/3} \quad (3)$$

where  $g$  is acceleration of gravity (m·s<sup>-2</sup>),  $S$  is slope gradient (m·m<sup>-1</sup>). In the WEPP model (Foster *et al.* 1995),  $f$  is the presence of soil surface characteristic. Models such as LISEM (De Roo *et al.* 1994) and EUROSEM (Morgan *et al.* 1998) use  $n$  to quantify the relationship between flow velocity and geometry in the channel. Zhang *et al.* (2003) found a linear function between flow velocity and sediment transport. Also, several hydraulic parameters (e.g., shear stress and stream power) are used to describe the erosion process by energy-based approaches. Nearing & Norton (1997) indicated that stream power was an appropriate predictor for soil detachment capacity. Moreover, most of the previous studies have been concerned with hydraulic properties of shallow flow and runoff hydraulic characteristics in rill erosion (Wang *et al.* 2015). However, relatively less knowledge is available regarding the relationship between nutrient transport and flow hydraulics in purple soil. Thus, it is necessary to analyze the flow hydraulics and the nutrient transport on purple soil slope. A better understanding of the relationship between flow hydraulics and nutrient losses will improve chemical transport modeling.

Approximately 800 million people worldwide depend directly on sloping croplands with a slope gradient >10° for sustenance (Drees *et al.* 2003). Many classifications of slope steepness for soil take 10° as a starting point for ‘steep slopes’ (Shi *et al.* 2012; Peng *et al.* 2015).

The farmlands in the Three Gorges Reservoir Area are distributed almost entirely across steep sloped land. We thus focused on steep slopes (e.g., slope gradient higher than 10°), which are typical in the Wangjiaqiao watershed, in combination with different rainfall intensities and with purple soil as the test sediment. The objectives of this study were: (i) to measure and analyze the production mechanism of surface flow, subsurface flow, and sediment based on rainfall simulations; (ii) to investigate the characteristics of total nitrogen (TN) loss in different pathways from runoff and sediments under varied slope gradients and rainfall intensities; and (iii) to investigate the relationship between TN transport and hydraulic parameters in purple soil. We hypothesized that the soil erosion processes and the associated nitrogen loss on the purple soil slope can be described in terms of the combination of rainfall intensity and slope gradient.

## MATERIALS AND METHODS

### Study sites and soil samples

Soil samples were collected from Wangjiaqiao watershed, Zigui County in Hubei province, China to study soil and nutrient loss in the sloped cropland. The region has a subtropical monsoon climate with a mean annual precipitation of 1,016 mm that occurs mostly between May and September. Slope gradients within the watershed range from 2° to 58° with an average of 23°. Selected soils were derived from purple sandy shales, which are the main parent materials in the study watershed. Based on the US Soil Taxonomy, they were classified into entisols. In order to analyze the soil erosion and the distribution of nutrient on sloping cropland under simulated rainfall conditions, soil samples were taken from a 0 to 40 cm soil layer of sloping cropland. To remove impurities such as stones and grass, the air-dried soil samples were sieved through a 5 mm mesh. Selected soil physical and chemical properties, shown in Table 1, were determined by standard methods described in ISSAS (1978). The size distribution of soil aggregates was measured by wet sieving with three replicates. Fifty grams of the soil samples were placed in the top of a set of sieves with 5.0, 2.0, 1.0, 0.5, and 0.25 mm pore openings from top to bottom. The sieve-set was placed on the shock rack of a Yoder aggregates analyzer, immersed in distilled water. Each sample was sieved for a duration of 30 min at a frequency of 30 min<sup>-1</sup> and 3 cm amplitude of the movement.

### Experiment setup

The study was carried out in the soil erosion laboratory. The experimental equipment (Figure 1) included a rainfall simulator (side-sprinkle rainfall simulating set-up) and the runoff plot (the soil flume was 3 m in length, 1 m in width, and 0.5 m in depth). The runoff plot is a soil flume with a

slope gradient adjustment device to allow the slope to be adjusted from 0 to 25°. Simulated rainfall was applied with lateral spraying nozzles parallel to the slope. The height of simulated rainfall was 16 m. The rainfall simulator can be set at any selected rainfall intensity ranging from 0.5 to 5.83 mm·min<sup>-1</sup> by adjusting the nozzles' aperture size and water pressure. The raindrop diameter distribution was 0.2 to 2 mm, and >85% of raindrop diameters were <1.0 mm. The raindrop kinetic energy distribution was 19.48 to 37.81 J/(m<sup>2</sup>·mm). Calibration of rainfall intensities was conducted before each experiment. A 'V'-shape trough was inserted at the soil surface and via plastic pipes, into a surface runoff collection container. The soil profile at the downslope end of the flume was covered with an aminoplastic web and the gap between the aminoplastic web and the bottom of the flume was filled with gravel (Jia *et al.* 2007). A trench about 0.05 m deep and 1 m wide was constructed at the bottom of the flume. The outlet of the trench was connected to a SSR collection container.

### Designs and measurements on rainfall simulation experiments

A total of 15 treatment combinations were performed. According to the rainfall statistical characteristics in Wangjiaqiao watershed, five different rainfall intensities (0.6, 1.1, 1.61, 2.12, and 2.54 mm·min<sup>-1</sup>) were selected for this study. These rainfall intensities were representative of the maximum 5-min precipitation ( $I_5$ ), the maximum 10-min precipitation ( $I_{10}$ ), the maximum 15-min precipitation ( $I_{15}$ ), the maximum 30-min precipitation ( $I_{30}$ ), and the maximum 60-min precipitation ( $I_{60}$ ) in the study watershed (Wang *et al.* 2010); approximately 2.54, 2.12, 1.61, 1.1, and 0.6 mm·min<sup>-1</sup>, respectively (the return period is 10-year), following a similar method as Shen *et al.* (2015), since high-intensity and short-duration rainstorms are primarily responsible for soil erosion in the Three Gorges Reservoir

**Table 1** | Physical-chemical properties of the study soils

Parent material	Bulk density (g cm <sup>-3</sup> )	Aggregate size distribution (%)						Organic matter (g kg <sup>-1</sup> )	Total N (g kg <sup>-1</sup> )
		>5 mm	5–2 mm	2–1 mm	1–0.5 mm	0.5–0.25 mm	<0.25 mm		
Purple sandy shale	1.35	4.09	10.48	12.38	8.01	7.48	57.56	5.60	0.37

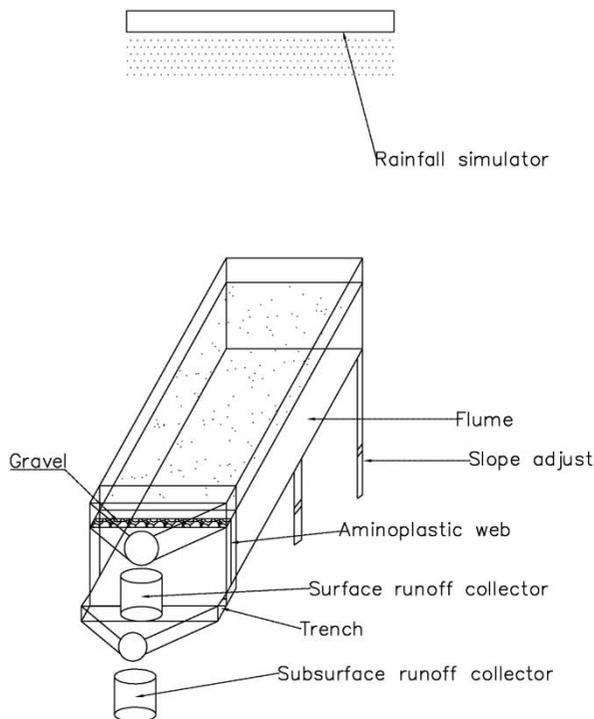


Figure 1 | Rainfall simulation experimental equipment.

Area, China. Three slope gradients ( $10^\circ$ ,  $15^\circ$ , and  $20^\circ$ ) were selected, representing typical slope gradients of the farmland of Wangjiaqiao watershed. Every simulated rainfall test was performed varying rainfall intensity but with a fixed rainfall volume of 50 mm. The duration of rainfall was controlled by the precipitation. The duration of rainfall was 83, 45, 31, 24, and 20 min for rainfall intensities of 0.6, 1.1, 1.61, 2.12, and  $2.54 \text{ mm}\cdot\text{min}^{-1}$ , respectively, following a similar method as Ding & Zhang (2016). Four indices were used to research the TN transport process, including surface (SR) and SSR volume, the loss characteristics of TN, and the sediment yield (S).

The soil sample was packed in the flume layer with 10 cm increments with a final height of 40 cm, and its sand, silt, and clay contents were 46%, 23%, and 31%, respectively. The bulk density of packed soil in the flume was  $1.35 \text{ g}\cdot\text{cm}^{-3}$ . Before each rain simulation, a known amount of rainfall was sprayed to minimize the differences in antecedent soil moisture. Both surface and SSR-collection pails at the flume outlet were changed periodically. At the beginning of runoff generation, samples were collected every 2 min. When the flow reached a stable state, the

sampling interval was set to 5 min. After each rainfall, the amount of runoff in each pail was weighed on a balance. The sediment was deposited in the pails, and then a siphon was used to transfer the supernatant into polyethylene bottles. Soil samples were air dried and weighed, and all samples were preserved in a refrigerator at  $4^\circ\text{C}$ ; analysis was complete within 24 h of collection. Sediment yield was determined as the dry sediment mass, while sediment yield rate was defined as dividing sediment yield per unit area by the period of time. All treatments were conducted in three replicates. All runoff samples were analyzed for TN, using standard methods (APHA 1985). For the sediment samples that were yielded from the plot, sediment TN was determined by the Kjeldahl method.

### Measurements of hydrodynamic parameters

Surface flow velocities ( $V_s$ ) were measured by the dye method. Three measured sections were set up along the flume length direction at 1-m intervals. The mean surface flow velocities were the average of the measured values at each section.  $V_s$  was used to estimate the profile average runoff velocity ( $V$ ) by the relation of  $V = nV_s$ , where  $n$  is a coefficient, laminar flow; it is 0.67 for laminar flow, 0.70 for transient flow, and 0.80 for turbulent flow (Abrahams et al. 1986).

The average flow depth was calculated from Equation (4):

$$h = \frac{Q}{VBt} = \frac{q}{V} \quad (4)$$

where  $h$  is mean flow depth (m),  $Q$  is surface runoff volume during  $t$  time (L), and  $q$  is the unit discharge of surface runoff ( $\text{m}^2\cdot\text{s}^{-1}$ ).

The hydraulic shear stress ( $\tau$ ) and stream power ( $W$ ) were calculated from Equations (5) and (6), respectively:

$$\tau = \rho ghS \quad (5)$$

$$W = \tau V = \rho ghSV \quad (6)$$

where  $\tau$  is the hydraulic shear stress ( $\text{N}\cdot\text{m}^{-2}$ ),  $\rho$  is the density of water ( $\text{kg}\cdot\text{m}^{-3}$ ), and  $W$  is the stream power ( $\text{N}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$ ).

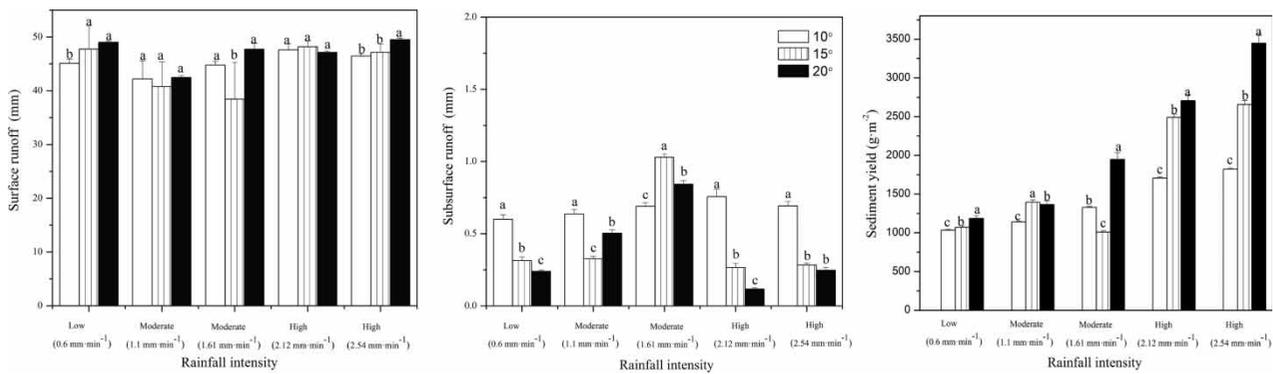
One-way analysis of variance (ANOVA) was used to analyze the difference of runoff and sediment and the least significant difference (LSD) method at the 0.05 probability level was used to identify statistical differences among treatments. The relationships between flow hydraulics and TN losses were analyzed by a simple regression method. All of these analyses were conducted using SPSS 20.0 software.

## RESULTS AND DISCUSSION

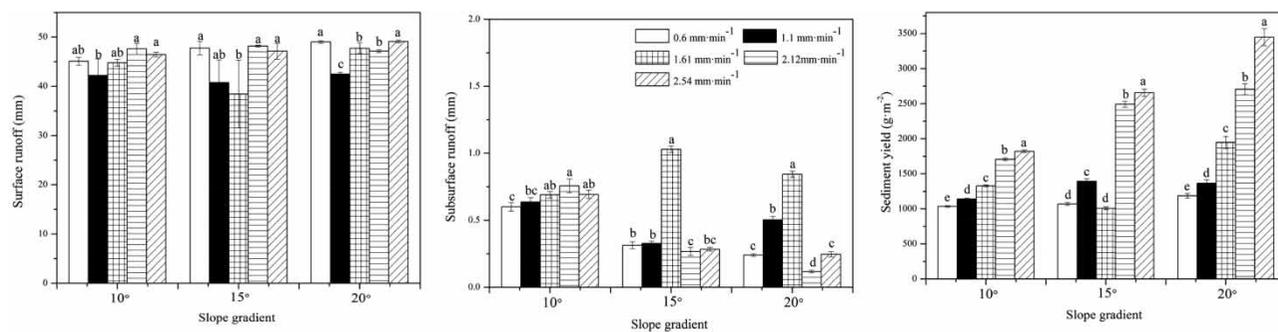
### Effects of rainfall intensity and slope gradient on runoff distribution and sediment concentration

The ANOVA showed that rainfall intensity and slope gradient had significant effects on runoff distribution and sediment yield. Mean surface runoff volume ranged from 38.6 to 49.1 mm (Figures 2 and 3). Surface runoff increased

with increasing slope gradient for low ( $0.6 \text{ mm}\cdot\text{min}^{-1}$ ) and high ( $2.12$  and  $2.54 \text{ mm}\cdot\text{min}^{-1}$ ) rainfall intensities. For moderate rainfall intensities ( $1.1$  and  $1.6 \text{ mm}\cdot\text{min}^{-1}$ ), surface runoff initially decreased to a minimum volume when the slope gradient was  $15^\circ$ , and then increased as the gradient increased further. Defersha & Melesse (2012) and Fang et al. (2015) found that the effects of slope and rainfall intensity on runoff and soil loss varied with soil type. In our experiment, surface runoff showed an decreasing-increasing trend as rainfall intensity increased. This may be associated with the physical properties of purple soil and effects of different rainfall intensity. Many studies indicate that soil surface sealing and rill development complicate runoff and erosion characteristics (Fang et al. 2015). Runoff discharge was increased when a seal was formed at the soil surface during rainfall (Assouline & Ben-Hur 2006). However, in this study where a seal layer is present at the soil surface, it seems that infiltration increases as rainfall intensity



**Figure 2** | Surface runoff volume, SSR volume, and sediment yield at various rainfall intensities. For each simulated rainfall intensity, means with the same lower-case letter are not significantly ( $P < 0.05$ , LSD) different.



**Figure 3** | Surface runoff volume, SSR volume, and sediment yield for different slope gradients. For each slope gradient, means with the same lower-case letter are not significantly ( $P < 0.05$ , LSD) different.

changed from low to moderate. Seal formation was less intense as rainfall intensity increased due to higher splash and sheet erosion, and increase of rill density and depth. Therefore, surface runoff decreased when the rainfall intensity changed from low to moderate. As rainfall intensity changed from moderate to high, infiltration excess runoff occurred when rainfall intensity exceeded the infiltration capacity. Consequently, surface runoff increased when the rainfall intensity changed from moderate to high. Moreover, average SSR volume ranged from 0.12 to 1.03 mm (Figures 2 and 3). Compared with the SSR, surface runoff for different slope gradients and simulated rainfall intensities was approximately 37.4 to 402.8 times the volumes for SSR. Furthermore, under the same slope gradient, SSR increased at first, then decreased as rainfall intensity increased. It is obvious that a long, low intensity rainfall can cause more SSR than a short high intensity rainfall (Jia *et al.* 2007).

According to Figures 2 and 3, the average sediment yield ranged from 1,008.13 to 3,447.77  $\text{g}\cdot\text{m}^{-2}$ . Both slope gradient and rainfall intensity had significant effects on the sediment yield. Sediment yield increased with increasing slope gradient. This pattern accorded with other studies (Defersha & Melesse 2012) in slope gradient and rainfall intensity increasing sediment yield. Ziadat & Taimah (2013) reported that rainfall intensity was the most important factor affecting soil erosion and that erosion could occur at a relatively small intensity on wet soils as a result of subsequent rainfall events. In this study, sediment yield was more sensitive to the rainfall intensity than the slope gradient. Under conditions of low (0.6  $\text{mm}\cdot\text{min}^{-1}$ ), moderate (1.1 and 1.61  $\text{mm}\cdot\text{min}^{-1}$ ), and high (2.12 and 2.54  $\text{mm}\cdot\text{min}^{-1}$ ) rainfall intensities, the sediment yield increased by 1.15, 1.19, 1.46, 1.58, and 1.89 times, respectively, as the slope gradients increased from 10° to 20°. On the other hand, for the slope gradients of 10°, 15°, and 20°, the sediment yield increased by 1.75, 2.48, and 2.91 times, respectively, as the rainfall intensities increased from 0.6 to 2.54  $\text{mm}\cdot\text{min}^{-1}$ .

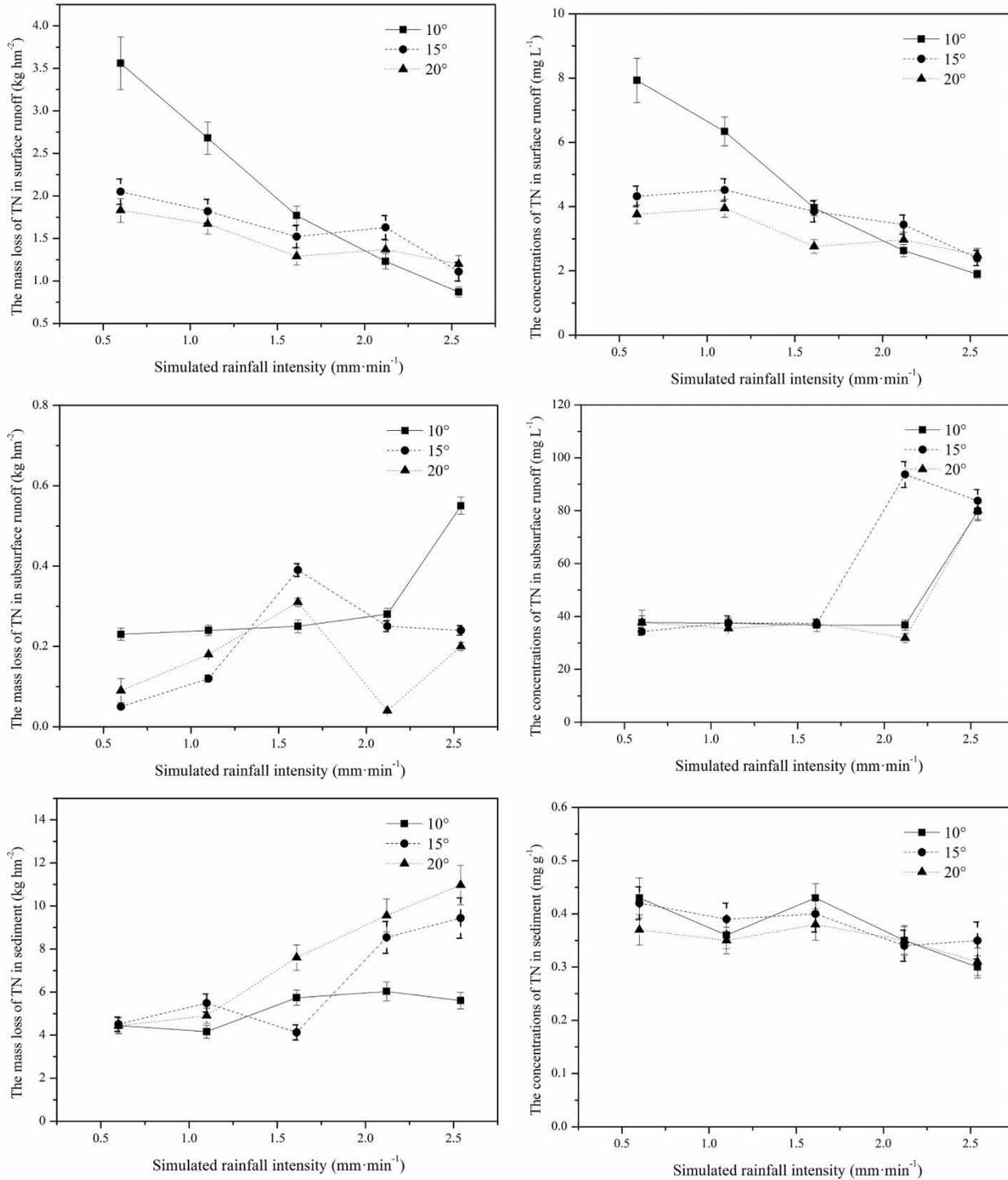
### Nitrogen losses in surface runoff, SSR, and sediment

The mass loss and concentrations of TN under different rainfall intensities and slope gradients are shown in Figure 4. In all three delivery mechanisms, the mass loss of TN

(M-TN) was greatest for the sediment delivery mechanism, intermediate for the surface runoff pathway, and least for the SSR pathway. The  $\text{M-TN}_S$  values ranged from 4.13 to 10.97  $\text{kg}\cdot\text{hm}^{-2}$ , the  $\text{M-TN}_{SR}$  values from 0.87 to 3.56  $\text{kg}\cdot\text{hm}^{-2}$ , and the  $\text{M-TN}_{SSR}$  values from 0.04 to 0.55  $\text{kg}\cdot\text{hm}^{-2}$ . Our results are different from those of Luo *et al.* (2009), who argued that in purple soil nitrogen is easily leached out to the interface of rock–soil, thus the sub-surface flow will carry more TN loss out of the soil at a slope gradient of 10°. The cause of these differences may be explained by the effective input water rate (greater rainfall intensities and steep slope gradients). There existed a critical slope of the purple soil slope, which was about 10°. Infiltration decreased greatly with slope when the slope was larger than the critical slope gradient (Qian *et al.* 2016). Moreover, an increase in slope gradient enhanced flow velocity and reduced the chance that runoff would be infiltrated into the soils (Fang *et al.* 2015). On steep slopes ranging from 10° to 20°, the influence of slope gradient on SSR volume was significant.

The range of M-TN values differed widely, and values did not show the same trend in all three delivery mechanisms. The mass of sediment-associated TN increases, and the mass of runoff-associated TN decreases, as the slope gradient increases. This may be due to the fact that nutrients such as nitrogen and phosphorus are basic components of the soil, which undergoes rainfall-driven erosion. Thus, the amount of nutrient loss is directly proportional to the amount of soil loss (Kothiyari *et al.* 2004). In addition, this may be associated with the particle selectivity of erosion of deposited sediment. Zhang *et al.* (2011) found that nutrients were mainly contained within the clay fraction. Researchers have reported that interrill erosion results in selective removal of clay and silt-sized particles (Pan *et al.* 2016a). Gilley *et al.* (2012) reported that nutrient desorption, which was an important control for runoff-associated nutrient loss, was limited by the contact time between runoff and the soil. The transport of clay and silt-sized particles increases, and the contact time between runoff and the soil decreases, as the slope gradient increases.

The concentration of TN (C-TN) was another major factor that influenced TN loss. As presented in Figure 4, the  $\text{C-TN}_S$ ,  $\text{C-TN}_{SR}$ , and  $\text{C-TN}_{SSR}$  values ranged from



**Figure 4** | The mass loss and concentrations of TN under different rainfall intensities and slope gradients.

$0.3$  to  $0.43\ \text{mg}\cdot\text{g}^{-1}$ ,  $1.90$  to  $7.93\ \text{mg}\cdot\text{L}^{-1}$ , and  $31.89$  to  $93.71\ \text{mg}\cdot\text{L}^{-1}$ , respectively. The average TN concentration in the SSR was over 12 times greater than that in the surface

runoff. The results are in agreement with many studies pertaining to the impacts of SSR on nitrogen transport (Pionke *et al.* 2000; Jia *et al.* 2007).

### Relationship between hydraulic properties and runoff-associated TN loss

Many studies have reported flow hydraulics (such as flow velocity, flow depth, and hydraulic roughness) are the major controlling factors of soil loss and nutrient transport (Fox & Bryan 2000; Guo *et al.* 2013). The hydraulic resistance is the important variable for predicting runoff hydraulic dynamics. Darcy–Weisbach friction coefficient ( $f$ ) is commonly used to model hydraulic resistance, and  $f$  is the most widely used because of its dimensionless expression and physical meaning (Luo *et al.* 2009). Thus,  $f$  was selected to be used for runoff-associated TN loss modeling. The relationship between resistance and water depth depends on the relative roughness ratio (Pan *et al.* 2016b). Soil erosion may be driven by soil characteristics which are determined by soil surface roughness and flow characteristics which contained water depth and velocity (Guo *et al.* 2013). The rate of Manning roughness coefficient to average flow depth ( $n/h$ ) representing both the soil and flow characteristics was a good indicator for explaining other hydraulic characteristics and could be used to predict soil erosion (Li *et al.* 2017). Therefore, the main hydraulic indicators were selected to be used for runoff-associated TN loss modeling. In order to compare those parameters, relationships between the unit area runoff-associated TN transport rate ( $MTN_R$ ), Reynolds numbers ( $Re$ ), shear stress, Darcy–Weisbach friction coefficient ( $f$ ), flow velocity ( $V$ ), stream power ( $W$ ), and the rate of Manning roughness coefficient to average flow depth ( $n/h$ ) are shown in Figure 5. As is shown, the unit area runoff-associated TN transport rate had positive linear relationships with Reynolds numbers, shear stress, stream power, and flow velocity and negative linear relationships with Darcy–Weisbach ( $f$ ) and the rate of Manning roughness coefficient to average flow depth. Also, our results indicated that among those hydraulic parameters, only  $n/h$  ( $R^2 = 0.71$ ) showed a good linear relationship with  $MTN_R$ , whereas  $Re$ ,  $f$ ,  $v$ ,  $w$ , and  $n$  were not good hydraulic indicators for the runoff-associated TN transport rate in the flume experiment.  $MTN_R$  was determined from the following equation:

$$MTN_R = \frac{0.0977 - 0.0012n}{h} (R^2 = 0.71) \quad (7)$$

This finding revealed that for purple soil at the small scale of the flume, the rate of Manning roughness coefficient to average flow depth could be used for runoff-associated TN loss. Similarly, Guo *et al.* (2013) found that the parameter of  $n/h$  was a good hydraulic parameter as an indicator for solute transport.

### Relationship between hydraulic properties and sediment-associated TN loss

Soil erosion is a process of detachment and transportation of soil materials by erosive agents. Sediment may serve as the delivery mechanism for nutrients (Shi *et al.* 2012). For the relationship between sediment yield rate and sediment-associated TN loss, regression analysis confirmed that a positive linear function resulted in the best fit (Figure 6). As is shown, the unit area sediment-associated TN transport rate ( $MTN_S$ ) had positive linear relationships with Reynolds numbers, shear stress, stream power, and flow velocity and negative linear relationships with Darcy–Weisbach and the rate of Manning roughness coefficient to average flow depth. Among the studied hydraulic parameters, Reynolds numbers showed the best performance in predicting  $MTN_S$  ( $R^2 = 0.90$ ), followed by flow velocity ( $R^2 = 0.87$ ), and stream power ( $R^2 = 0.73$ ). In contrast, shear stress, Darcy–Weisbach, and the rate of Manning roughness coefficient to average flow depth had no acceptable performance in estimating  $MTN_S$  due to low coefficient of determinations. This finding reveals that for purple soil at the small scale of the flume, Reynolds numbers could be used for modeling sediment-associated TN transport.  $MTN_S$  was determined from the following equation:

$$MTN_S = -0.034 + 3.491 \times 10^{-4} Re (R^2 = 0.90, p = 0.00) \quad (8)$$

In most process-based erosion models, stream power has been used for predicting soil detachment (Nearing & Norton 1997). Stream power can be used to illustrate the effect of both the slope gradient and runoff rate during soil loss (Huang 1995). As mentioned previously, the slope gradient and rainfall intensity were recognized as the main controlling factors of slope soil erosion. Thus,

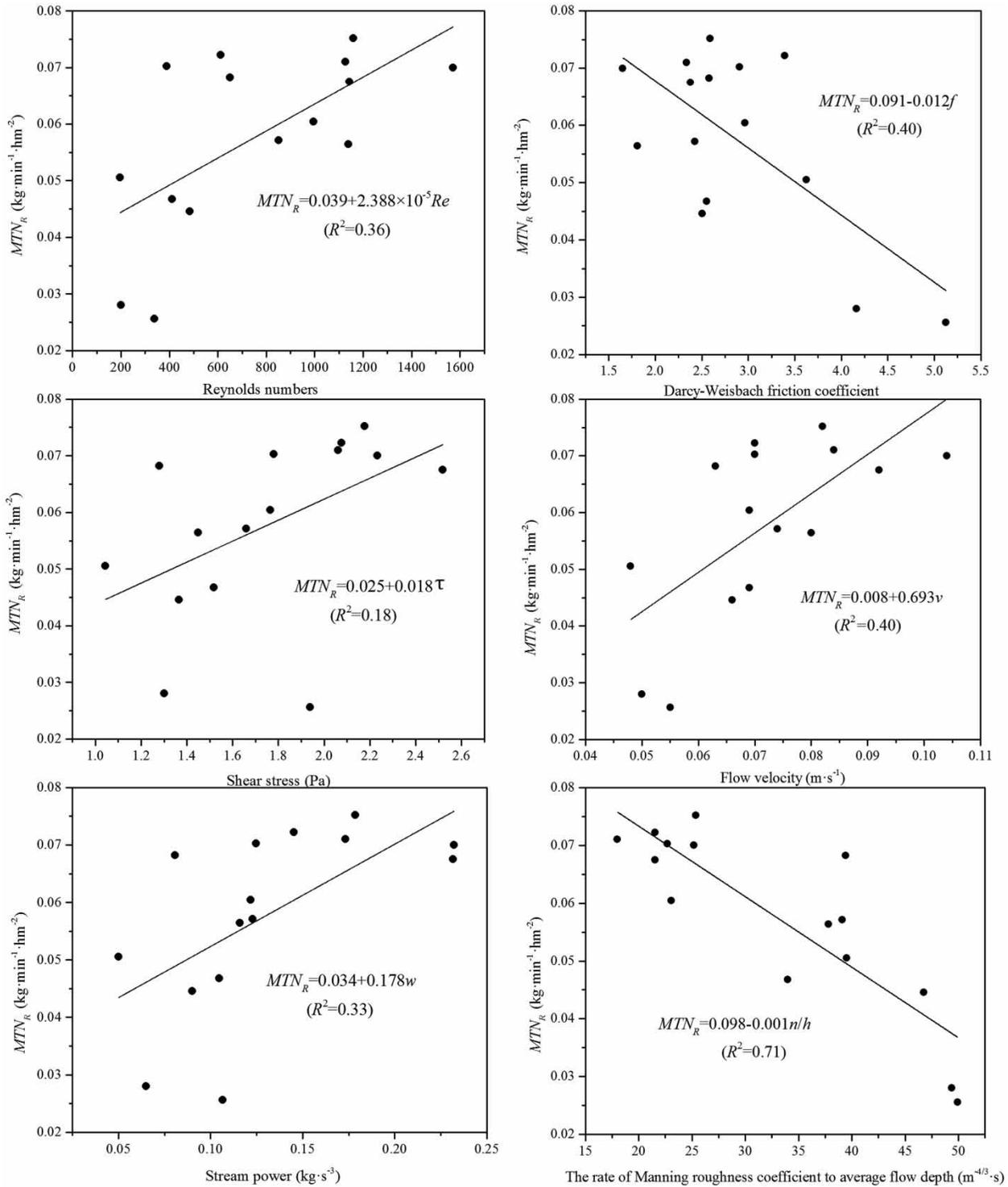
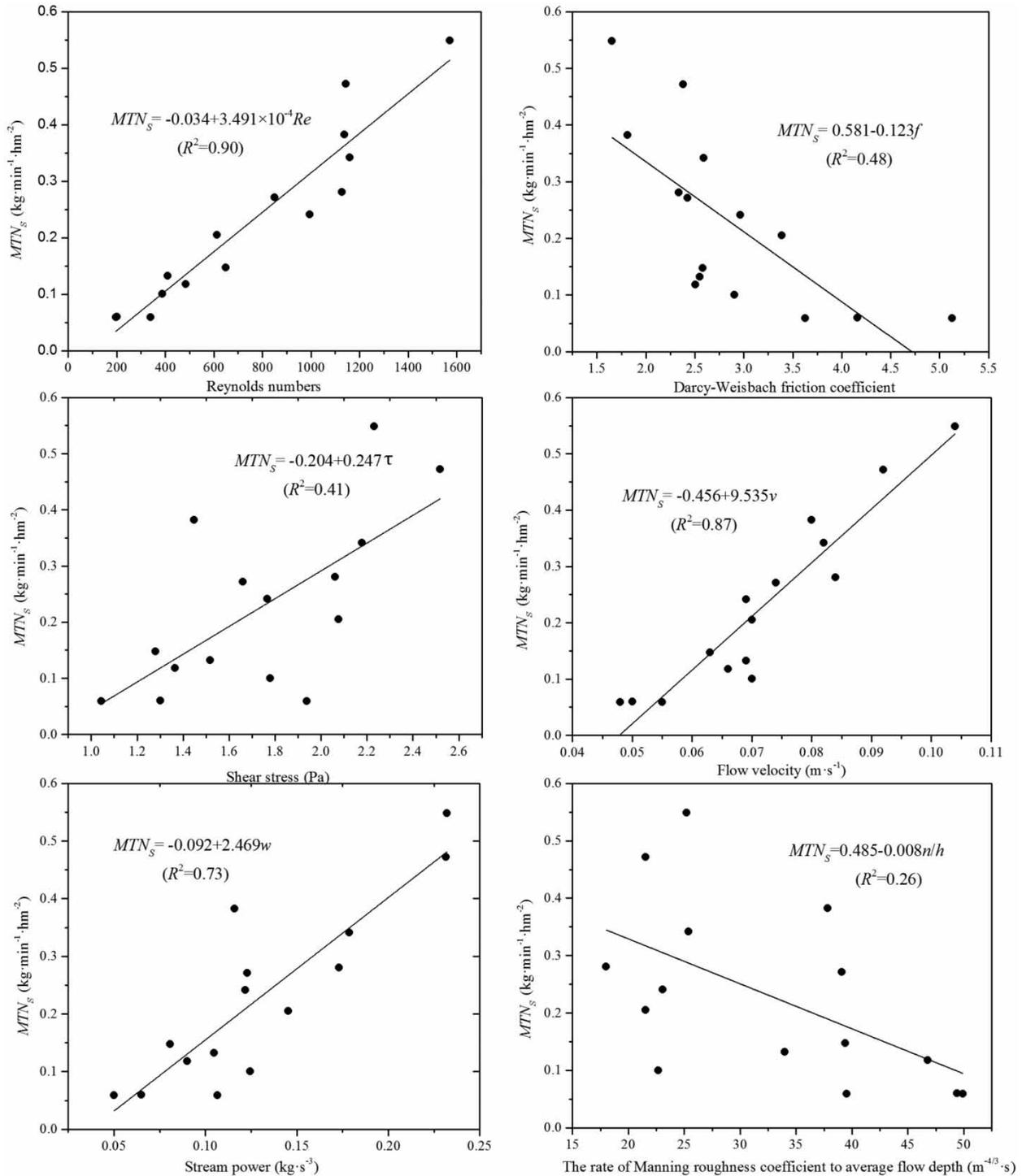


Figure 5 | Relationship between the unit area runoff-associated TN transport rate ( $MTN_R$ ) and hydraulic parameters.

the combination of slope gradient and rainfall intensity affected sediment-associated TN transport. Moreover, flow velocity is an essential determinant of transport of

nutrients (Carleton & Mohamoud 2013). Fox & Bryan (2000) indicated that flow velocity increases the transport capacity of overland flow. However, they are not



**Figure 6** | Relationship between the unit area sediment-associated TN transport rate ( $MTN_s$ ) and hydraulic parameters.

considered in the impact of stream power and the average flow velocity on TN transport. It seemed desirable to take into account stream power and the average flow velocity in

sediment-associated TN loss model. Both stream power and flow velocity had significant effects on  $MTN_s$  (Figure 6).

A new equation for the unit area sediment-associated TN transport rate was obtained:

$$MTN_S = 2.199 \times 10^{-4} Re + 0.302W + 2.929V - 0.186$$

$$(R^2 = 0.94, p = 0.00) \quad (9)$$

The statistical model, Equation (9), may provide a better correlation coefficient ( $R^2 = 0.94$ ) than Equation (8) ( $R^2 = 0.90$ ) for estimating sediment-associated TN transport rate in purple soil.

The results of the current study indicate that TN transport was closely related to the rate of Manning roughness coefficient to average flow depth, Reynolds numbers, stream power, and flow velocity. Equations (7) and (9) were convenient and effective for predicting runoff-associated TN transport rate and sediment-associated TN transport rate, respectively. However, some studies found that particle size characteristics of sediments are important for controlling the off-site effects of sediment-bounded nutrients (Novara *et al.* 2013). Fine soil particles are readily transported by overland runoff (Issa *et al.* 2006). Palis *et al.* (1990) reported that fine soil particles are usually richer in soil-sorbed nutrients than are coarse sediments. Further studies should be conducted to investigate the effects of rainfall intensity on temporal change in eroded soil particles and sediment-bound nutrient loss.

## CONCLUSIONS

This study investigated the loss characteristics of TN and the relationship between flow hydraulics and TN losses within a rainfall simulation system at various rainfall intensities and steep slope gradients. The results showed that surface runoff volume ranged from 38.6 to 49.1 mm, which was 37.4 to 402.8 times that for SSR. The average TN concentration in the SSR was over 12 times greater than that in the surface runoff. A high correlation between the rate of Manning roughness coefficient to average flow depth and the unit area runoff-associated TN transport rate ( $R^2 = 0.71$ ) indicated that flow hydraulics are the major controlling factors of runoff-associated TN transport. Moreover, a significant positive linear relationship between sediment

yield rate and  $MTN_S$  was obtained ( $R^2 = 0.98$ ) indicating that sediment-associated TN transport was driven by soil loss. In this study, the main hydraulic indicators were selected to be used for sediment-associated TN loss modeling. Among the studied hydraulic parameters, Reynolds numbers ( $R^2 = 0.90$ ), flow velocity ( $R^2 = 0.87$ ), and stream power ( $R^2 = 0.73$ ) showed a good linear relationship with the unit area sediment-associated TN transport rate, whereas  $Fr$ ,  $f$ , and  $n/h$  were not good hydraulic indicators for the sediment-associated TN loss on purple soil erosion. The statistical model, Equation (9) (including stream power and flow velocity), provides a better correlation coefficient ( $R^2 = 0.94$ ) than Equation (8) ( $R^2 = 0.90$ ) for estimating sediment-associated TN transport rate in purple soil. The results can be used to improve the mechanisms of soil erosion and the effects of different pathways on nutrient loss.

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