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# Evaluation of shear stress and unit stream power to determine the sediment transport capacity of loess materials on different slopes

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**Abstract**

*Purpose* This study aims to evaluate the relationship between loess soil-based sediment transport capacity and the most well-known and extensively used shear stress and unit stream power for different steep slopes. This study also determined the suitability of shear stress- and unit stream power-based transport capacity functions for rill flow on non-erodible bed.

*Materials and methods* Loess soil was collected from Ansai County, which is located in a typical loessial region in China's Loess Plateau. The median diameter of the loess soil was 0.04 mm. The experiment was conducted in a rill flume with a soil-feeding hopper. The slope gradients in this study ranged from 10.51 to 38.39%, and the flow discharges per unit width varied from $1.11 \times 10^{-3}$ to $3.78 \times 10^{-3}$ $m^2$ $s^{-1}$. The sediment transport capacity was measured for each combination.

*Results and discussion* Results showed that $T_c$ can be effectively described by the power function shear stress-based equations for various slope gradients with $R^2 > 0.94$ and $P < 0.01$. Shear stress was a good predictor of $T_c$ for different slope gradients with the Nash–Sutcliffe model efficiency (NSE) from 0.94 to 0.99. Moreover, shear stress was better in predicting $T_c$ when the slope gradient was above 21.26%. $T_c$ can be efficiently described by the power function unit stream power-based equations for various slope gradients with $R^2 > 0.95$ and $P < 0.01$. Unit stream power was a good predictor of $T_c$ for different slope gradients with NSE that ranged from 0.95 to 0.99. The unit stream power predicted $T_c$ better when the slope gradient was above 26.79%. Unit stream power was more satisfied than shear stress for predicting $T_c$ under different slope gradients. The unit stream power-based LISEM, which was multiplied by 0.62 (i.e., the correction coefficient), predicted well the sediment transport capacity of the rill flow in our experiment, where NSE = 0.93. The shear stress-based Zhang model, which was multiplied by the correction coefficient of 0.77, adequately predicted the sediment transport capacity of rill flow in our experiment, where NSE = 0.81.

*Conclusions* By performing the controlled rill flume experiments, this study showed that shear stress and unit stream power strongly influenced $T_c$ for certain slope gradients under non-erodible conditions.

**Keywords** Loess soil · Rill flow · Sediment transport capacity · Shear stress · Unit stream power

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## 1 Introduction

Soil erosion is a global environmental problem and has been the concern of many researchers (Lal 1998; Vigiak et al. 2005;

Wang et al. 2015). Many soil erosion models, such as the kinematic runoff and erosion model (KINEROS2) (Smith et al. 1995), Limburg soil erosion model (LISEM) (De Roo et al. 1996), European soil erosion model (EUROSEM) (Morgan et al. 1998), and water erosion prediction project (WEPP) (Flanagan et al. 2001), have been developed. These models are extensively used to assess the sediment yield at catchment scale. Soil erosion is a combination of soil detachment and soil transport; the latter is a sub-process of soil erosion. Hence, sediment transport capacity plays a vital role in the physical description of soil erosion processes. In addition, the accurate evaluation of sediment transport capacity in susceptible areas is necessary to the development of process-based soil erosion models.

In recent decades, numerous investigations have been conducted to calculate sediment transport capacity by overland flow. The suitability of different transport capacity equations has been assessed under different experimental conditions. Researchers determined that hydrodynamic parameters, particularly shear stress and unit stream power, have considerable influence on sediment transport capacity. A majority of the available overland flow transport capacity functions were derived using shear stress and unit stream power under erodible and non-erodible conditions. Govers (1990) suggested that shear stress could be used to predict sediment transport capacity under erodible conditions. The WEPP model uses a modified Yalin equation (Yalin 1963) to calculate sediment transport capacity. In the WEPP model, sediment transport capacity is a power function of shear stress. Abrahams et al. (2001) determined that shear stress effectively predicts sediment transport capacity under non-erodible condition. Zhang et al. (2009) also suggested that sediment transport capacity can be predicted well by shear stress under non-erodible conditions. Sediment transport capacity is calculated as follows:

$$T_c = 0.054\tau^{1.982}, \quad (1)$$

where $T_c$ is the sediment transport capacity (kg $m^{-1}$ $s^{-1}$) and $\tau$ is shear stress (Pa).

Researchers have also determined that unit stream power has the best relationship with the measured sediment transport capacity for overland flow under erodible beds. Govers and Rauws (1986) suggested that unit stream power could sufficiently predict sediment transport capacity. Govers (1992) considered that in specific cases, a simple empirical equation based on the unit stream power could be used to predict the sediment transport capacity of overland flow. Ali et al. (2011) performed flume experiments with sand as the soil material. The result showed that unit stream power is an optimal composite force predictor that could estimate transport capacity for shallow flows. However, for non-erodible beds, researchers obtained different results on the relationship between unit stream power and sediment transport capacity. Zhang et al. (2009) suggested that sediment transport capacity is predicted poorly by unit stream power. Wang et al. (2015) used a rill flume to analyze the relationship between sediment transport capacity and hydraulic parameters and determined that unit stream power is a poor predictor of sediment transport capacity on steep slopes. LISEM (De Roo et al. 1996), which is based on the equation reported by Govers (1990, 1992), models $T_c$ as a function of unit stream power. The sediment transport capacity is calculated as follows:

$$T_c = d_s m(P{-}P_c)^n, \quad (2)$$

where $T_c$ is the sediment transport capacity in LISEM (kg $m^{-3}$)$T_c = q\gamma_s m(P - P_C)^n$; $ds\gamma_s$ is the mass density of the test soil (=2650 kg $m^{-3}$); $m$ and $n$ are coefficients calculated as $m = [(d_{50} + 5)/0.32]^{-0.6}$ and $n = [(d_{50} + 5)/300]^{0.25}$, where $d_{50}$ is the median particle diameter of the test soil (μm) and P is the unit stream power (W $N^{-1}$); and $P_c$ is the critical unit stream power (W $N^{-1}$).

In the LISEM, $T_c$ with the unit of kg $m^{-3}$ was described by unit stream power. In the Zhang model, $T_c$ with the unit of kg $m^{-1}$ $s^{-1}$ was used instead of $T_c$ with the unit of kg $m^{-3}$, which could be obtained from the unit of kg $m^{-1}$ $s^{-1}$ divided by the per unit width sediment-laden flow discharge with the unit of $m^2$ $s^{-1}$.

Govers (1992) explained that no existing equation could perform well when several equations are tested using experimental data obtained under laboratory conditions that simulate rill flow because of different hydraulic conditions. Ali et al. (2013) analyzed the suitability of five extensively used transport capacity equations under overland flow conditions and determined that existing functions are not in good agreement with the measured results. Several researchers derived empirical functions to quantify the transport capacity under different conditions (Govers and Rauws 1986; Govers 1990; Everaert 1991; Smith et al. 1995). However, only a few studies determined the $T_c$ of rill flow using loess sediments and steep slopes (Wang et al. 2015; Wu et al. 2016). Wang et al. (2015) suggested that $T_c$ was more sensitive to flow discharge than slope gradient. Wu et al. (2016) considered that stream power was good to predict $T_c$. This condition exists in the Loess Plateau in northwest China. Hence, conducting experiments under this condition is necessary to obtain an improved understanding of the soil erosion process in this region.

The objectives of this study are to evaluate the relationship between sediment transport capacity and the most well-known and extensively used shear stress and unit stream

Table 1 The particle size fraction of test soil

| | Particle size fraction | | | |
|---|---|---|---|---|
| | Clay (0–0.002 mm) | Silt (0.002–0.05 mm) | Very fine sand (0.05–0.1 mm) | Fine sand (0.1–0.25 mm) |
| Mean values (%) | 10.02 | 53.41 | 30.35 | 6.04 |
| Standard errors | 0.6 | 6.3 | 1.9 | 0.3 |

Where the particle size fraction of test soil based on the soil particle size classification system of the US Department of Agriculture

power for different slope, as well as to verify the suitability of shear stress- and unit stream power-based transport capacity functions for rill flow on non-erodible bed.

## 2 Materials and methods

### 2.1 Test soil

Test soil is loess soil collected from Ansai County which is located in a typical loessial region in China's Loess Plateau. The particle size fraction of test soil is shown in Table 1. The median diameter of the loess soil was 0.04 mm. The contents of the water stable soil aggregates, which were measured using a wet sieve method, comprised 1.88% (1–2 mm), 2.50% (0.5–1 mm), 3.62% (0.25–0. 5 mm), and 91.97% (<0.25 mm). The loess soil was air dried and sieved through a 2-mm sieve to remove small stones and weeds before experiment.

### 2.2 Experimental setup

The experiment was conducted in the Simulated Soil Erosion Experiment Hall of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, CAS & MWR, Yangling. Experiment device is 4 m × 0.1 m × 0.1 m (length × width × depth) rill flume used to measure $T_c$. The surface of the rill flume bed was evenly glued to the test soil to maintain constant roughness. The slope of the rill flume was adjusted using a stepping motor that enabled the adjustment of the bed gradient to 57.73%. At the upstream end of the rill flume, an overflow groove was



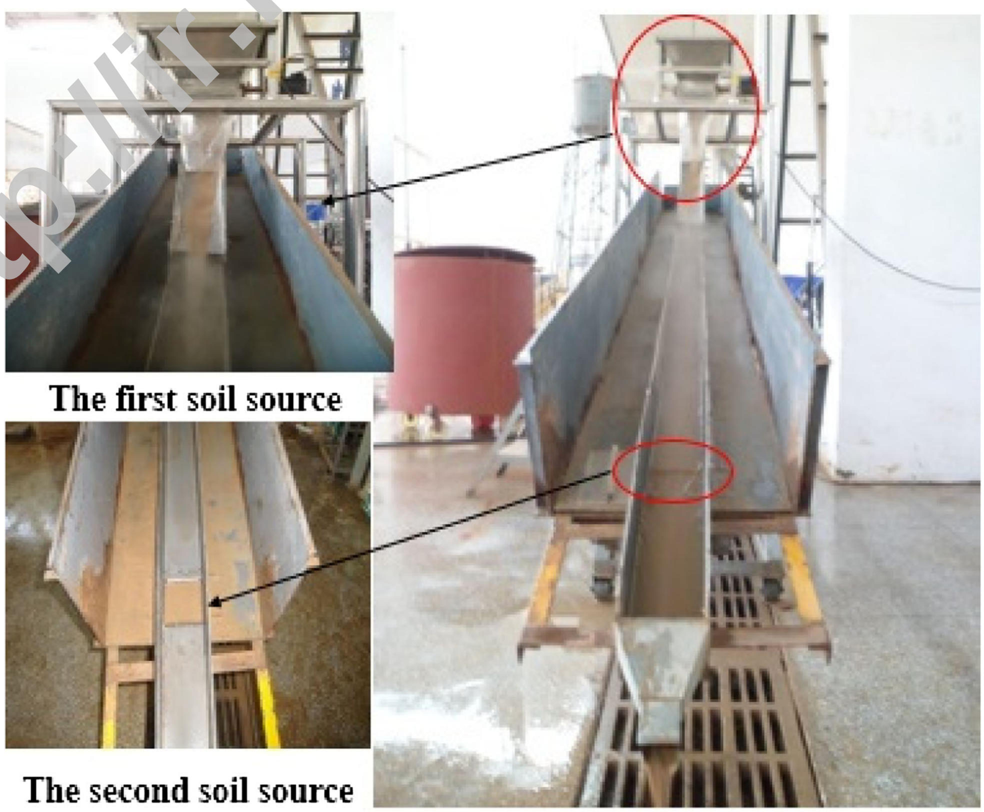



Fig. 1 The rill flume used to measure sediment transport capacity on different slopes

**Table 2** The experiment design

| Slope gradient (%) | Flow discharge($10^{-3}$ m$^2$ s$^{-1}$) | Combinations |
|---|---|---|
| 10.51 | 1.11, 1.56, 2.00, 2.44, 2.89, 3.33,3.78 | 7 |
| 15.84 | 1.11, 1.56, 2.00, 2.44, 2.89, 3.33,3.78 | 7 |
| 21.26 | 1.11, 1.56, 2.00, 2.44, 2.89, 3.33,3.78 | 7 |
| 26.79 | 1.11, 1.56, 2.00, 2.44, 2.89, 3.33,3.78 | 7 |
| 32.49 | 1.11, 1.56, 2.00, 2.44, 2.89, 3.33,3.78 | 7 |
| 38.39 | 1.11, 1.56, 2.00, 2.44, 2.89, 3.33,3.78 | 7 |
| | | Total = 42 |

installed for supplied water from tap water system overflowing into the rill flume to become rill flow. Flow discharge of rill flow was controlled by a series of valves installed on water pipe, which connect tap water system and overflow groove, and was measured by a calibrated flow meter.

Two soil sources were designed to ensure that $T_c$ could be determined throughout all the experiments. The first supplied soil source was a hopper installed above the upstream end of the rill flume. The soil feeding rate was controlled by the rotational speed of the rotors installed within the hopper, and the rotational speed of the rotors was controlled by adjusting the drives. The relationship between feeding rate and rotational speed of the rotors was calibrated before the experiment. The second supplied soil source was a box filled with the test soil embedded in the downstream end of the rill flume (see Fig. 1). The size of the box filled with soil was 0.2 m × 0.1 m × 0.1 m (length × width × depth). The box filled with soil has a series of small holes at its bottom and must be put in a water container for soil saturated for 24 h before experiment. This approach assumes that the particles are not limited at source or are sufficiently supplied, and thus, the transport capacity of the rill flow can be accurately measured as transport capacity of the rill flow is the maxium of particles transported by rill flow, which can be obtained only when the particles are not limited at source or are sufficiently supplied for transporting of rill flow.

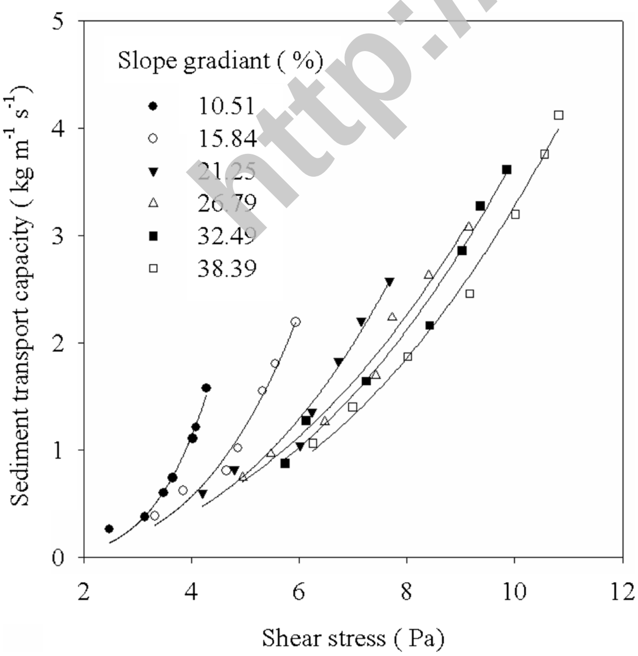



**Fig. 2** The relationship of $T_c$ with shear stress on six slope gradients

### 2.3 Experimental procedures

The slope of the flume bed and flow discharge were adjusted to the desired values prior to feeding the loess soil. After the flow discharge was stabilized, the second soil source was covered substantially with a thin iron sheet, and the measurement of flow depth and flow velocity was started. The hopper began feeding the test soil to the flow of the rill flume after the flow depth and flow velocity were measured. The soil feeding rate was gradually adjusted by changing the rotational speed of the rotors until the feeding sediment could not be carried completely. $T_c$ was assumed to have been reached, and the soil feeding rate was set. Thereafter, the iron sheet was removed and measurements of $T_c$ were performed. If $T_c$ was not reached because of insufficient soil fed from the hopper, then the deficit of the soil was added from the second sediment source to reach $T_c$. Five samples were collected at the downstream end of the rill flume with a specific time interval as rapidly as possible for each combination of flow rate and slope

**Table 3** Statistical equations of sediment transport capacity (y) by rill flow varying with shear stress (x) under different slopes and statistical evaluation of these new equations based on observed and predicted values

| Slope gradient (%) | Statistical equation | $R^2$ | MSE | NSE | $P$ |
|---|---|---|---|---|---|
| 10.51 | $y = 0.0111 \times^{3.3005}$ | 0.94 | 0.14 | 0.94 | < 0.01 |
| 15.84 | $y = 0.011 \times^{2.9339}$ | 0.97 | 0.12 | 0.96 | < 0.01 |
| 21.26 | $y = 0.0184 \times^{2.3921}$ | 0.95 | 0.15 | 0.95 | < 0.01 |
| 26.79 | $y = 0.0177 \times^{2.3288}$ | 0.98 | 0.11 | 0.99 | < 0.01 |
| 32.49 | $y = 0.0139 \times^{2.4197}$ | 0.98 | 0.11 | 0.99 | < 0.01 |
| 38.39 | $y = 0.013 \times^{2.3975}$ | 0.99 | 0.1 | 0.99 | < 0.01 |

Where $R^2$ is the coefficient of determination, MSE is the residual mean, and NSE is the coefficient of Nash-Suticliffe model efficiency

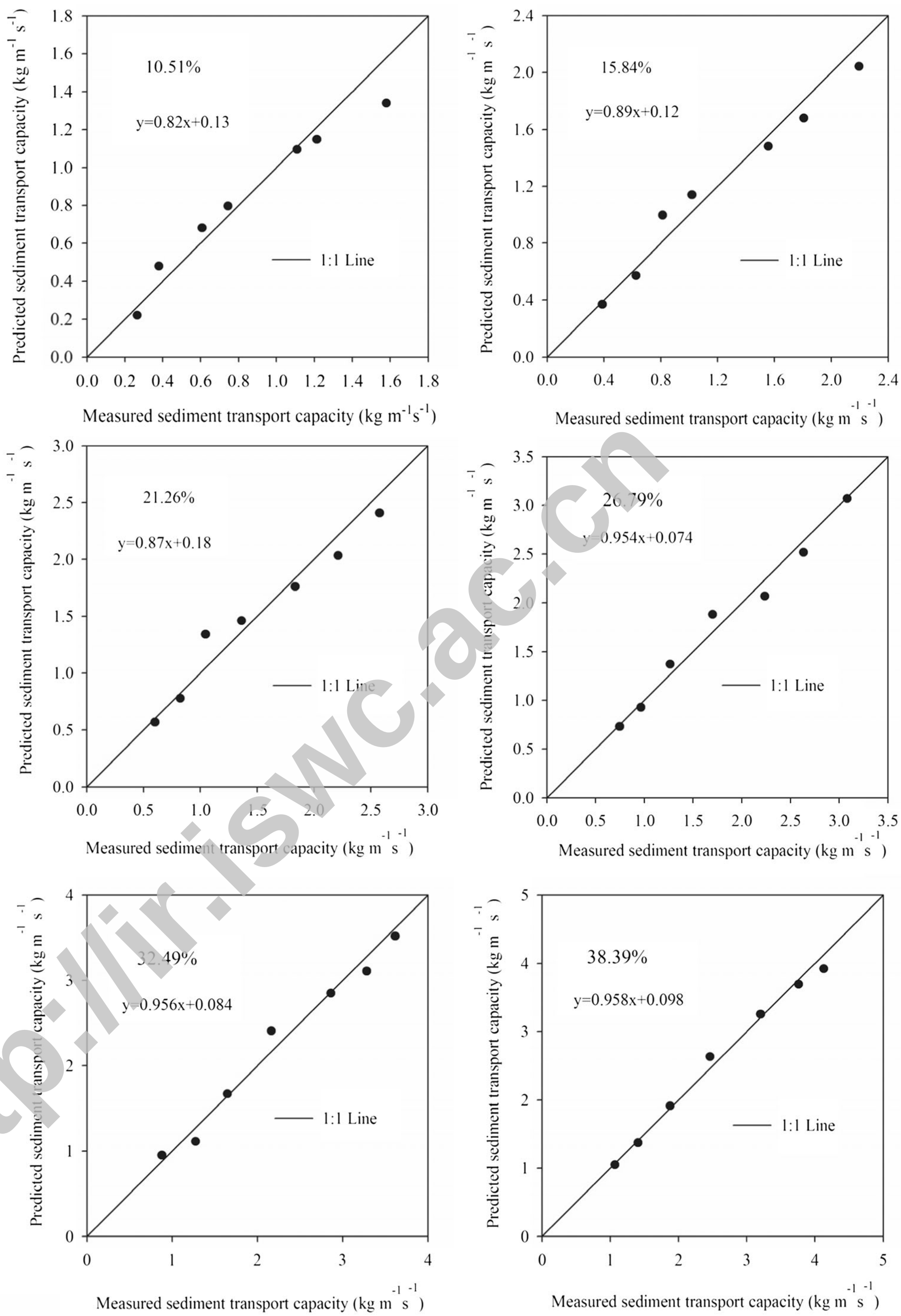



**Fig. 3** Measured vs. predicted sediment transport capacity (using shear stress-based equations from Table 3)



gradient. The collected samples were allowed to settle for 24 h. The clear supernatant was decanted from the containers, and the wet sediment was oven dried at 105 °C for 12 h. The weight of the dry sediment was divided by the sampling time and flume width to obtain $T_c$. The average of the five samples was used as the measured equilibrium $T_c$ for the combination of flow discharge and slope gradient. A series of 42 combinations of flow discharges and slope gradients were tested (Table 2).

## 2.4 Measurements and calculations

### *2.4.1 Flow depth*

Flow depth measurements were taken using a level probe with an accuracy of 0.2 mm at cross point of left, middle, and right which is 0.08, 0.05, and 0.02 m from the right wall of rill flume and upside, middleside, and downside which is 2, 62, and 122 cm from the upstream end of second supplied soil source

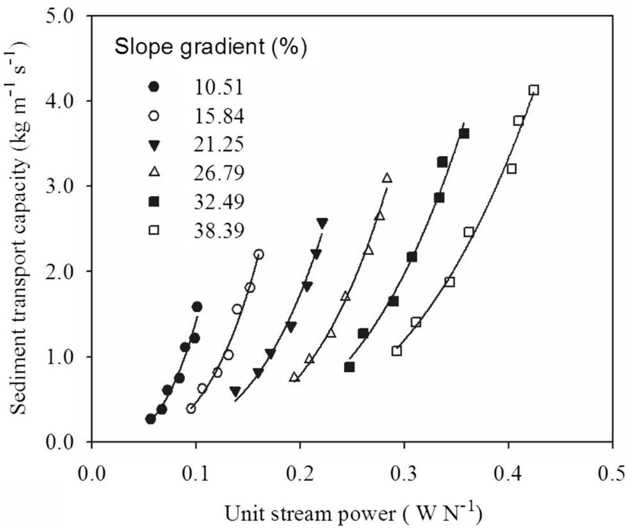



**Fig. 4** The relationship of $T_c$ with unit stream power on six slope gradients

of the rill flume, respectively. Nine depths were measured for each combination of flow discharge and slope gradient; the measurement of each combination was repeated once. The average of 18 depths was considered as the mean flow depth for the combination of flow discharge and slope gradient. The mean flow depth was used to calculate the shear stress ($\tau$).

*2.4.2 Flow velocity*

Flow velocity was measured using $KMnO_4$ as tracer. The time during which the tracer was required to traverse in marked distance (i.e., 0.6 m) was determined based on the color-front propagation using a stop watch. Flow velocity was measured twice, and three flow velocity values were obtained from the left, middle, and right across the flow section of the experiment flume with a width of 0.1 m. A total of six flow velocity values were used to calculate the surface flow velocity. Mean flow velocity of water layer was obtained by multiplying the surface flow velocity by 0.70 when the flow was transitional and by 0.80 when the flow was turbulent (Grag et al. 1996; Li et al. 1996; An et al. 2012). The mean flow velocity was used to calculate unit stream power (P).

**Table 4** Statistical equations of sediment transport capacity (y) by rill flow varying with unit stream power (x) under different slopes and statistical evaluation of these new equations based on observed and predicted values

| Slope gradient (%) | Statistical equation | $R^2$ | MSE | NSE | P |
|---|---|---|---|---|---|
| 10.51 | $y = 1298 \times^{2.968}$ | 0.97 | 0.13 | 0.95 | < 0.01 |
| 15.84 | $y = 876 \times^{3.273}$ | 0.95 | 0.12 | 0.97 | < 0.01 |
| 21.26 | $y = 225.5 \times^{3.028}$ | 0.98 | 0.11 | 0.98 | < 0.01 |
| 26.79 | $y = 301.2 \times^{3.672}$ | 0.99 | 0.09 | 0.99 | < 0.01 |
| 32.49 | $y = 183 \times^{3.769}$ | 0.98 | 0.07 | 0.99 | < 0.01 |
| 38.39 | $y = 87.66 \times^{3.57}$ | 0.99 | 0.08 | 0.99 | < 0.01 |

Where $R^2$ is the coefficient of determination, MSE is the residual mean, and NSE is the coefficient of Nash-Suticliffe model efficiency

*2.4.3 Shear stress*

The shear stress is calculated as (Yalin 1963):

$$\tau = \rho g h S, \tag{3}$$

where $\tau$ is the shear stress (Pa), $\rho$ is the water mass density (kg $m^{-3}$), $g$ is the gravitational constant (m $s^{-2}$), $h$ is the flow depth (m), and $S$ is the sine of the bed slope (m $m^{-1}$).

*2.4.4 Unit stream power*

The unit stream power is calculated as follows (Yang 1972, 1973):

$$P = VS, \tag{4}$$

where $P$ is the unit stream power (W $N^{-1}$), $V$ is the mean velocity (m $s^{-1}$), and $S$ is the sine of the bed slope (m $m^{-1}$).

### 2.5 Evaluation of equations

Statistical parameters $R^2$, MSE, and NSE values were used to evaluate the performance of new equations. $R^2$, MSE, and NSE values were calculated as follows:

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(O_i - \overline{O}\right)\left(P_i - \overline{P}\right)\right]^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2 \sum_{i=1}^{n}\left(P_i - \overline{P}\right)^2}, \tag{5}$$

$$\text{MSE} = \sqrt{\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}}, \tag{6}$$

$$\text{NSE} = 1 - \frac{\sum(O_i - P_i)^2}{\sum\left(O_i - \overline{O}\right)^2}, \tag{7}$$

where $R^2$ is the coefficient of determination, MSE is the residual mean, and NSE (Nash and Sutcliffe 1970) is a normalized statistic that reflects the relative magnitude of the residual variance compared with the variance of the observed data [good (NSE > 0.7), satisfactory (0.4 < NSE ≤ 0.7), and unsatisfactory (NSE ≤ 0.4)] (Moriasi et al. 2007; Ahmad et al. 2011; An et al. 2012). $O_i$ are the observed values, $P_i$ are the predicted values, $\overline{O}$ is the mean of the observed value, and $\overline{P}$ is the mean of the predicted value.

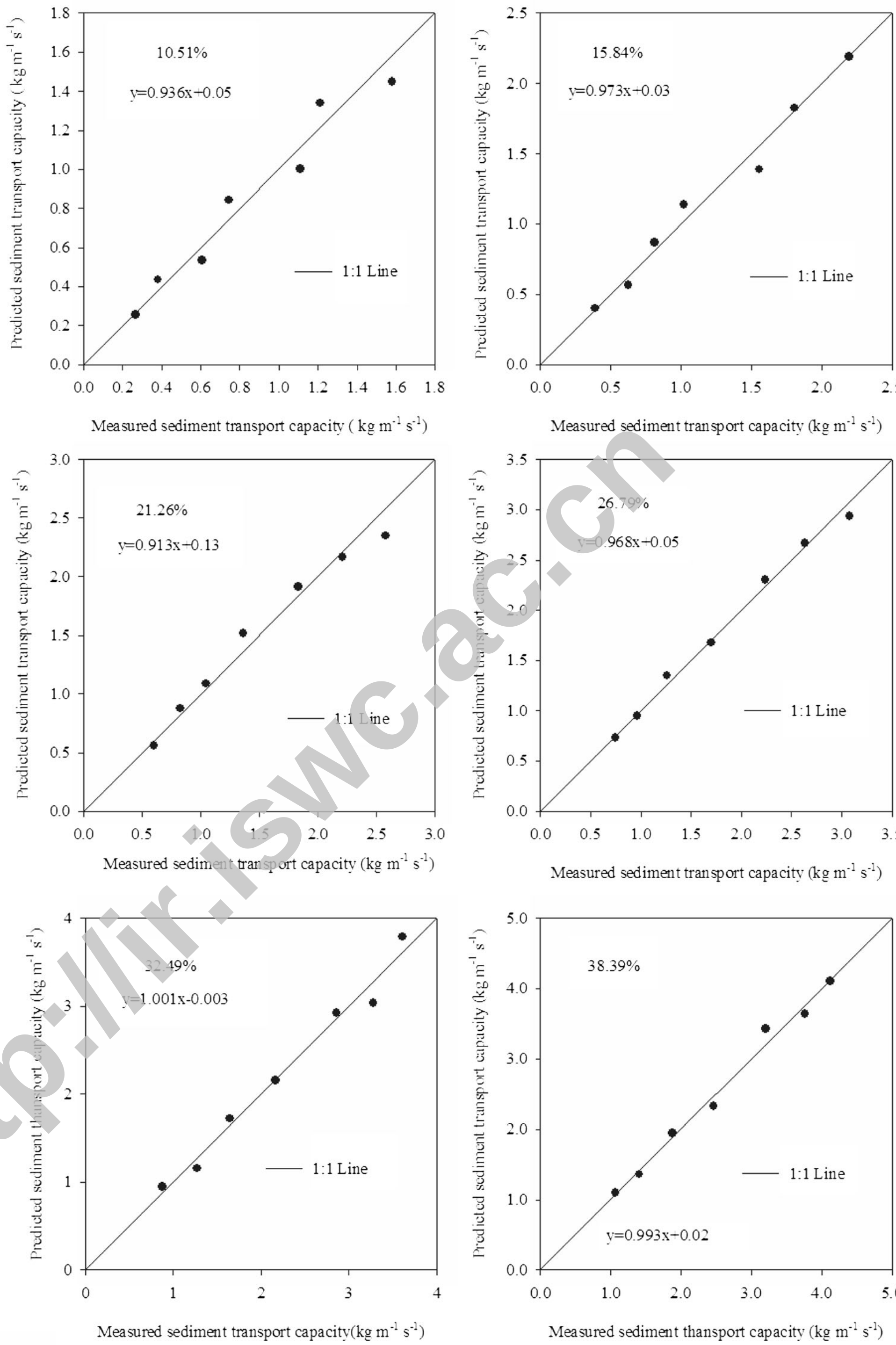



**Fig. 5** Measured vs. predicted sediment transport capacity (using unit stream power-based equations from Table 4)

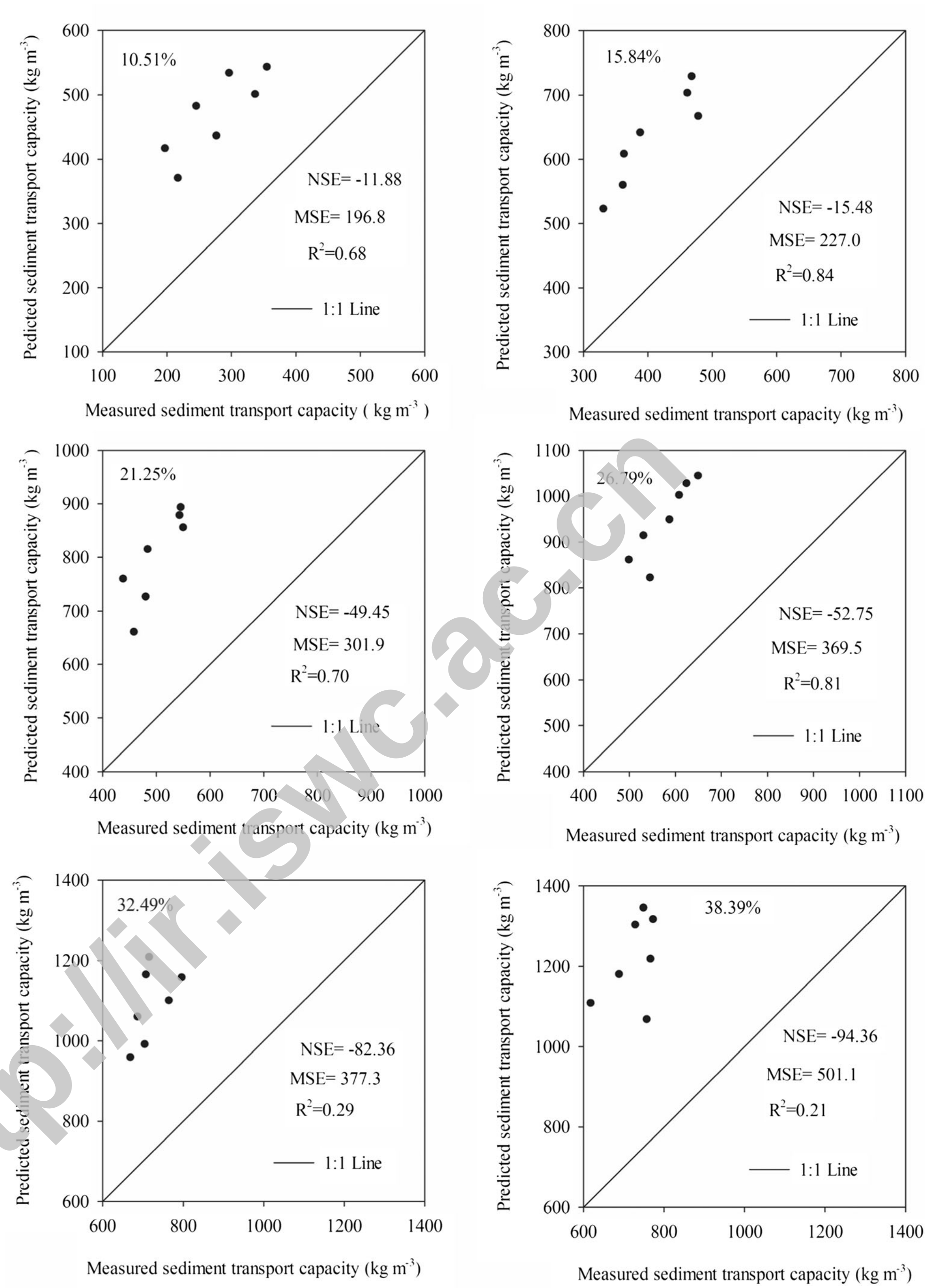


## 3 Results and discussion

### 3.1 Relationship of $T_c$ with shear stress and unit stream power on different slopes

Figure 2 shows the relationship of $T_c$ with shear stress on six slope gradients. In the experiment, the measured $T_c$ increased with increasing shear stress for every slope gradient. Several researchers suggested that sediment transport capacity increases as a power function with flow discharge (Beasley and Huggins 1982; Prosser and Rustomji 2000; Zhang et al. 2009; Mahmoodabadi et al. 2014). In addition, shear stress was estimated in the equation of Yalin (1963; Nearing et al. 1989), thereby resulting into shear stress increasing with the increase

**Fig. 6** Measured vs. predicted sediment transport capacity on different slopes (using LESEM)






in flow discharge. Hence, shear stress had a positive influence on sediment transport capacity. However, although Fig. 2 also shows $T_c$ increase with shear stress increasing, increasing rate is different under different slope gradient. These results can be explained by the following statements. First, the slope gradient has a positive influence on shear stress (Yalin 1963; Nearing et al. 1989). Second, the test soil material in the current study was loess sediments obtained from Ansai, Shaanxi in China, and this soil is different from the sands selected by many researchers (Aziz and Scott 1989; Li and Abrahams 1999; Li et al. 2011). Third, the water stable aggregates of the loess sediments may have an important influence on sediment transport capacity.

Table 3 shows that variation of $T_c$ with shear stress can be described effectively by power function equations for various slope gradients with $R^2 > 0.94$ and $P < 0.01$, and shear stress was a good predictor of $T_c$ for different slope gradients with NSE from 0.94 to 0.99 and $R^2$ from 0.94 to 0.99 and MSE from 0.1 to 0.14. Figure 3 also shows that the predicted $T_c$ is extremely close to the measured values. The results are in agreement with those reported in previous studies (Low 1989; Guy et al. 1992; Govers 1992; Zhang 2009). In the present experiment, the shear stress was a better predictor of $T_c$ when the slope gradient was above 21.26%.

Figure 4 shows that the measured $T_c$ varied with the unit stream power on different slope gradients. Evidently, unit stream power strongly influenced the measured $T_c$. In particular, the measured $T_c$ increased rapidly with increasing unit stream power for different slope gradients. Table 4 shows that variation of $T_c$ with unit stream power can be described clearly by power function equations for various slope gradients with $R^2 > 0.95$ and $P < 0.01$, and the unit stream power was a good predictor of $T_c$ for different slope gradients with NSE from 0.95 to 0.99 and $R^2$ from 0.95 to 0.99 and MSE from 0.07 to 0.13. Figure 5 also shows that the predicted $T_c$ is extremely close to the measured values. These results are in agreement with some studies in the literature (Govers and Rauws 1986; Moore and Burch 1986; Govers 1990; de Roo et al. 1996; Ali et al. 2011), but disagree with Zhang et al. (2009) and Wang et al. (2015) for which unit stream power was not a good predictor. The results from this study is different from Zhang et al. (2009) and Wang et al. (2015), which are likely caused by the different hydraulic condition (Govers 1992) and test materials. The test material in the study reported by Zhang et al. (2009) is sand, which is different from the test material in our study. Although the test material in the study reported by Wang et al. (2015) is the same as the test material which is loess sediment in our study, the flow discharges in the study reported by Wang et al. (2015) were far less than the flow discharges in our study. In addition, the unit stream power predicted $T_c$ better when the slope gradient was above 26.79%; thus, $T_c$ was satisfactorily predicted by the unit stream power on steep slopes in our study.

### 3.2 Predicting $T_c$ using LISEM and the Zhang model

To evaluate the suitability of LISEM and the Zhang model in our experiment, we compared the measured $T_c$ versus the predicted values using both models (Figs. 6 and 7). Figure 6 shows that the predicted sediment transport capacities calculated using LISEM were higher than the measured values of all the slope gradients. The average of the values of $T_c$ predicted using LISEM were 468.94, 632.80, 798.12, 945.38, 1091.28, and 1291.63 kg m$^{-3}$ for the six slope gradients; the average of measured $T_c$ obtained in the experiment were 275.12, 407.64, 500.29, 578, 721.15, and 726.51 kg m$^{-3}$. NSE for the LISEM-predicted values decreased with increasing slope gradient from −11.88 to −94.36 and MSE for the LISEM-predicted values decreased with increasing slope gradient from 196.8 to 501.1 and $R^2$ for the LISEM-predicted values changed from 0.21 to 0.84. The negative values of NSE, MSE, and $R^2$ mean that the model performance as a predictor was not as good as that when the mean of the observations was used (Yu and Rosewell 2001). Accordingly, LISEM (De Roo et al. 1996) was ineffective in predicting the sediment transport capacity of rill flow in our experiment, and the model performance on the steep slopes has limited effectiveness. Although Govers (1990, 1992) found unit stream power to be a good predictor of sediment transport capacity, its use in the LISEM equation was not a good predictor for the experimental results of this study. The variation in these results is probably caused by experimental conditions, test materials, and grain size. Loess soil is different from well-sorted sand, and the median particle diameter (i.e., 0.04 mm) in our study is smaller than its counterparts (i.e., 0.058, 0.127, 0.218, 0.414, and 1.098 mm) in the study of Govers (1990). Thus, the prediction of sediment transport capacity obtained by the existing model developed from observations is questionable (Govers 1992). However, by the regression analysis between results of our experiment and results calculated by LISEM, the correction coefficient can be reformulated to improve LISEM's predictive capability to determine the sediment transport capacity of the rill flow. Figure 7 shows that if a correction coefficient of 0.62 is applied to the LISEM equation, the corrected LISEM equation effectively predicted the sediment transport capacity of the rill flow in our experiment with NSE = 0.93, MSE = 44.8, and $R^2$ = 0.93.

Figure 8 shows the predicted values of $T_c$ derived by the Zhang model compared with the measured values. The predicted values were higher than the measured values when the slope gradient was above 15.83%. Moreover, the Zhang model poorly predicted the sediment transport capacity with NSE changed from 0.35 to −1.35 and MSE from 0.55 to 1.7 and $R^2$

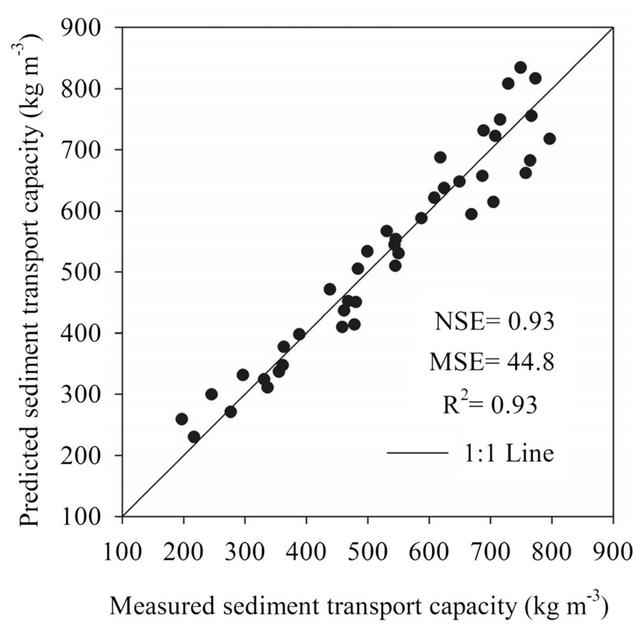



**Fig. 7** Measured vs. predicted sediment transport capacity (using corrected LESEM)

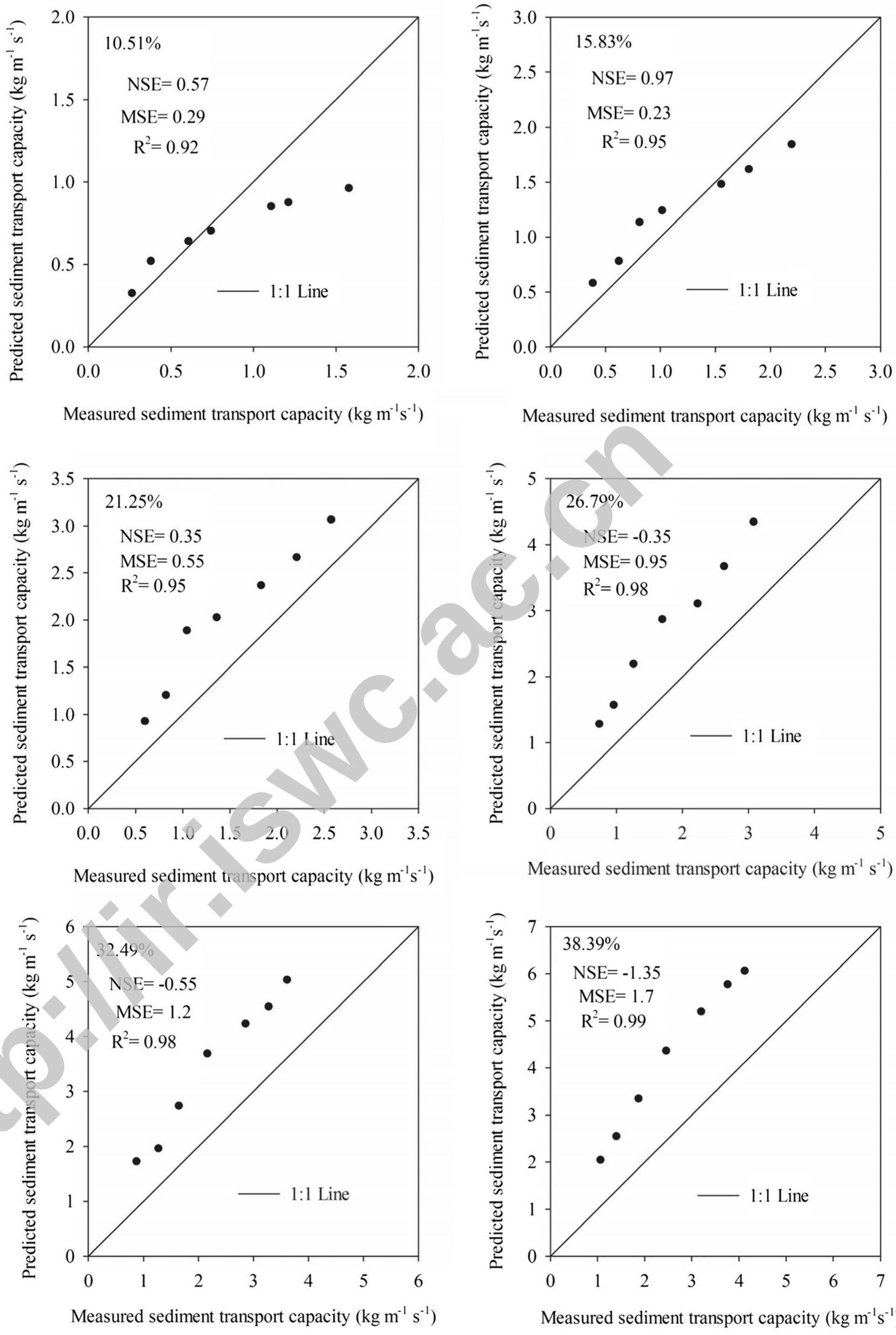



**Fig. 8** Measured vs. predicted sediment transport capacity on different slopes (using Zhang model)



from 0.95 to 0.99 as the slope gradient increased from 21.25 to 38.39%. For the slope gradient of 10.51 and 15.83%, NSE of Zhang's model were 0.57 and 0.97 and MSE were 0.29 and 0.23, respectively, indicating the predictive power of the Zhang model was good at a slope of 15.83%, but worsened as the slope increased or decreased. Thus, the predictive power of the Zhang model was not effective over the full range of experimental conditions. Zhang (2009) reported that the measured sediment transport capacity can be considerably simulated by shear stress with a power function; the equation (i.e., the Zhang model) can substantially predict sediment transport capacity with NSE = 0.97 on a relatively steep slope of 15.83%. However, in our study, the Zhang model failed to considerably predict the sediment transport capacity when the slope gradient was above 15.83%. The flow discharge and slope gradient in our study are similar to those reported by

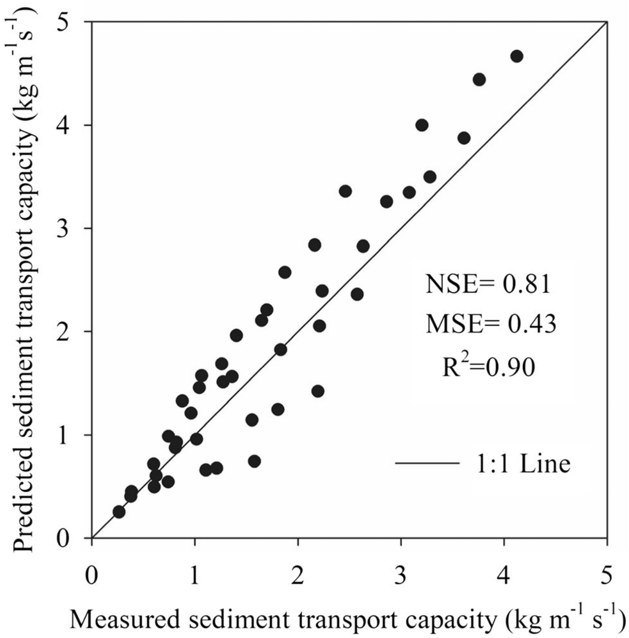



**Fig. 9** Measured vs. predicted sediment transport capacity (using corrected Zhang model)

Zhang (2009), and the only difference is the experimental material. Liu et al. (2007) reported that at an unsteady state, the rate of sediment transported by flow depends on the soil and hydraulic characteristics. Thus, our results may be explained by two factors. First, the test soil in our study was loess sediments obtained from Ansai, Shaanxi in China, whereas the test material reported by Zhang (2009) was well sorted sand collected from the bed of the Yongding River near Beijing. The median particle diameter (i.e., 0.04 mm) of our sample was 600% smaller than its counterpart (0.28 mm) in the study of Zhang (2009). Second, the contents of water stable soil aggregates have a positive influence on sediment transport capacity.

Similarly, by the regression analysis between results of our experiment and results calculated by Zhang model, the correction coefficient can be reformulated to improve Zhang model's predictive capability to determine the sediment transport capacity of the rill flow. The 1:1 line of measured vs. predicted sediment transport capacity using corrected Zhang model (Fig. 9) shows that the Zhang model multiplied by the correction coefficient of 0.77 effectively predicted the sediment transport capacity of the rill flow in our experiment with NSE = 0.81, MSE = 0.43, and $R^2$ = 0.90.

## 4 Conclusions

By performing the controlled rill flume experiments, this study showed that shear stress and unit stream power strongly influenced $T_c$ for certain slope gradients under non-erodible conditions. $T_c$ increased as a power function with shear stress and unit stream power. In addition, shear stress was a good predictor of $T_c$ for fixed slope gradient with NSE from 0.94 to 0.99 and $R^2$ from 0.94 to 0.99 and MSE from 0.1 to 0.14 and was substantially sensitive to $T_c$ when the slope gradient was over 21.26%. Moreover, unit stream power was a good predictor of $T_c$ for the designed slope gradients with NSE from 0.95 to 0.99 and $R^2$ from 0.95 to 0.99 and MSE from 0.07 to 0.13. A few of studies showed that unit stream power poorly predicted $T_c$ with considerably low NSE. Thus, the contents of water stable aggregates in our study may have significantly influenced $T_c$.

LESEM and the Zhang model, which used unit stream power and shear stress, are the widely used models for predicting $T_c$. The predicted sediment transport capacities calculated using LISEM were higher by 62% than the measured values for our study conditions. While the LISEM model was a poor predictor of $T_c$ for our study conditions, using a correction factor of 0.62 improved its predictive capability, with a NSE of 0.93. The Zhang model based on shear stress was a poor predictor of $T_c$, particularly on steeper slopes. However, when the slope gradient was from 10.51 to 15.83%, the predictive power of the Zhang model based on shear stress improved with the NSE increase from 0.57 to 0.97. When the slope gradient was above 15.83%, the Zhang model performed poorly in predicting $T_c$. Moreover, with the slope increase, NSE of the Zhang model changed from 0.35 to −1.35 and using a correction factor (0.77) improved the predictive capability to a NSE of 0.81 for the study conditions. These significant findings showed that the flow discharge, slope gradient, grain size, and experiment bed were not the only factors that exerted a sensitive influence on the sediment transport capacity. The soil type, particularly the contents of water stable aggregates, exerted such influence as well. Overall, the existing model can facilitate the prediction of the sediment transport capacity under our study conditions. However, this model should be used judiciously. Thus, firstly, the additional research is needed to develop equations/models that can be universally applied to predict sediment transport capacity; secondly, the suitability of the widely used models should be evaluated in different experiment conditions, which can help to obtain different correction factors to predict sediment transport capacity.

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