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Guang-Hui Zhang [a] [b] , Li-Li Wang [b] , Ke-Ming Tang [b] , Rong-Ting Luo [b] & X. C. Zhang [c]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences, Yangling, Shaanxi, 712100, China

[b] School of Geography, Beijing Normal University, Beijing, 100875, China

[c] USDA-ARS Grazinglands Research Laboratory, El Reno, Oklahoma, USA

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Effects of sediment size on transport capacity of overland flow on steep slopes

Guang-Hui Zhang[1,2], Li-Li Wang[2], Ke-Ming Tang[2], Rong-Ting Luo[2] & X. C. Zhang[3]

[1]*State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences, Yangling, Shaanxi 712100, China*
ghzhang@bnu.edu.cn

[2]*School of Geography, Beijing Normal University, Beijing 100875, China*

[3]*USDA-ARS Grazinglands Research Laboratory, El Reno, Oklahoma, USA*

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Abstract Sediment transport capacity is a key concept in determining rates of detachment and deposition in process-based erosion models, yet limited studies have been conducted on steep slopes. We investigated the effects of sediment size on transport capacity of overland flow in a flume. Unit flow discharge ranged from 0.66 to 5.26×10^{-3} m^2 s^{-1}, and slope gradient varied from 8.7 to 42.3%. Five sediment size classes (median diameter, d_{50}, of 0.10, 0.22, 0.41, 0.69 and 1.16 mm) were used. Sediment size was inversely related to transport capacity. The ratios of average transport capacity of the finest class to those of the 0.22, 0.41, 0.69 and 1.16 mm classes were 1.09, 1.30, 1.55 and 1.92, respectively. Sediment transport capacity increased as a power function of flow discharge and slope gradient ($R^2 = 0.98$), shear stress ($R^2 = 0.95$), stream power ($R^2 = 0.94$), or unit stream power ($R^2 = 0.76$). Transport capacity generally decreased as a power function of sediment size (exponent $= -0.35$). Shear stress and stream power predicted transport capacity better than unit stream power on steep slopes when transport capacity was <7 kg m^{-1} s^{-1}. Sediment transport capacity increased linearly with mean flow velocity. Critical or threshold velocity increased as a power function of sediment size ($R^2 = 0.93$). Further studies with fine soil particles are needed to quantify the effects of sediment size on transport capacity of overland flow on steep slopes.

Key words erosion; transport capacity; sediment size; overland flow; steep slope

Effets de la taille des sédiments sur la capacité de transport du ruissellement sur les pentes abruptes

Résumé La capacité de transport des sédiments est un concept clé dans la détermination des taux de détachement et de dépôt dans les modèles d'érosion à base physique, mais peu d'études ont été menées sur des pentes abruptes. Nous avons étudié les effets de la taille des sédiments sur la capacité de transport du ruissellement dans un canal. Le débit variait de 0.66 à 5.26×10^{-3} m^2 s^{-1}, et l'inclinaison variait de 8.7 à 42.3%. Cinq classes de taille des sédiments (diamètre médian, D_{50}, de 0.10, 0.22, 0.41, 0.69 et 1.16 mm) ont été utilisées. La capacité de transport s'est révélée être inversement proportionnelle à la taille des sédiments. Les ratios de capacité moyenne de transport de la classe la plus fine à celles des classes 0.22, 0.41, 0.69 et 1.16 mm ont respectivement été de 1.09, 1.30, 1.55 et 1.92. La capacité de transport des sédiments augmente en fonction du débit et de la pente ($R^2 = 0.98$), de la contrainte de cisaillement ($R^2 = 0.95$), de la puissance du courant ($R^2 = 0.94$), ou de la puissance unitaire du courant ($R^2 = 0.76$). La capacité de transport a généralement diminué algébriquement en fonction de la taille des sédiments (exposant $= -0.35$). La contrainte de cisaillement et la puissance du courant prévoient une capacité de transport du flux unitaire plus importante sur les pentes abruptes où la capacité de transport était <7 kg m^{-1} s^{-1}. La capacité de transport des sédiments augmente linéairement avec la vitesse moyenne d'écoulement. La vitesse critique augmente selon une loi puissance en fonction de la taille des sédiments ($R^2 = 0.93$). D'autres études avec des particules de sol fines sont nécessaires pour quantifier les effets de la taille des sédiments sur la capacité de transport du ruissellement sur les pentes abruptes.

Mots clefs érosion; capacité de transport; taille des sédiments; ruissellement; pente abrupte

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INTRODUCTION

In most process-based erosion models (Nearing *et al*. 1989, De Roo *et al*. 1996, Morgan *et al*. 1998), sediment transport capacity, which is the maximum equilibrium sediment load that a flow can transport, is specified as an independent quantity (Guy *et al*. 2009a). Transport capacity determines rates of detachment and deposition and the spatial distribution of erosion in many erosion models. Soil detachment occurs only when the sediment load is less than the transport capacity corresponding to the flow, and deposition occurs when the sediment load exceeds this transport capacity (Nearing *et al*. 1989). Precise prediction of sediment transport capacity of overland flow is critical for adequate prediction of soil erosion.

Sediment transport capacity of overland flow is primarily a function of flow hydraulics. Erosion researchers have formulated predictive equations using different hydraulic variables to compute sediment transport capacity. Flow discharge and slope gradient are frequently used, because they are fundamental drivers of transport capacity (Julien and Simons 1985, Guy *et al*. 2009b) and can be measured directly in both laboratory and field (Beasley and Huggins 1982, Prosser and Rustomji 2000, Zhang *et al.* 2009). Sediment transport capacity increases as a power function of either flow discharge or slope gradient, and the exponents of both flow discharge and slope gradient have been shown to vary within a range of 0.9 to 1.8, with a mean of 1.4 (Prosser and Rustomji 2000).

The mean flow velocity is another important variable affecting sediment transport capacity, because it is affected by both flow hydraulics (flow discharge, slope, roughness, sediment load, and flow depth) and surface conditions (vegetation cover and drainage condition). Sediment transport capacity increases linearly with mean flow velocity. Sediment is set into motion when flow velocity is greater than threshold velocity (Zhang *et al*. 2009). However, the potential effect of sediment size on threshold velocity on steep slopes is unknown.

Shear stress is commonly used to compute sediment transport capacity of overland flow (Yalin 1963, Foster and Mayer 1972, Alonso *et al*. 1981, Julien and Simons 1985, Finkner *et al*. 1989). Transport capacity was found to increase as a power function of shear stress. A power of 1.5 was adopted in the simplified transport capacity equation of the Water Erosion Prediction Project (WEPP) model (Nearing *et al*. 1989). However, some other studies showed that the exponent should be greater than 1.5 (Trout 1999, Zhang *et al*. 2008, Nord *et al*. 2009).

Bagnold (1966) changed the emphasis from forces applied to the bed (shear stress) to the rate of energy expenditure, expressing sediment transport capacity as a function of stream power per unit bed area. Some studies showed that stream power was the best hydraulic variable to estimate sediment transport capacity of overland flow (Bagnold 1980, Li and Abrahams 1999, Abrahams *et al.* 2001). The concept of stream power was adopted in the Griffith University Erosion System Template (GUEST) model to estimate the sediment transport capacity of overland flow (Yu *et al*. 1997).

Unit stream power was also used by Yang (1972) to develop a total load equation for cohesionless natural sands. Several studies revealed that sediment transport capacity was closely related to unit stream power (Govers 1990, 1992, Shih and Yang 2009). The latter concept is currently used in the EUROSEM (European Soil Erosion Model) (Morgan *et al*. 1998) and LISEM (Limberg Soil Erosion Model) (De Roo *et al*. 1996) erosion models.

Sediment transport capacity is also strongly influenced by sediment properties, such as sediment size, density, shape and roughness (Young 1980, Low 1989, Govers 1992, Guy *et al*. 2009a, Nord *et al*. 2009). The influences of sediment size and density are included in some equations of transport capacity (Agarwal 1989, Low 1989, Everaert 1991, Govers 1992), but the effects of sediment shape and roughness are not considered. Many equations are valid only for specific ranges of sediment size and density (Guy *et al*. 2009a). Agarwal (1989) demonstrated an inverse relationship between transport capacity and particle size for three materials with d_{50} ranging from approximately 0.015 to 0.75 mm. Low (1989) found that the effects of sediment size and density on transport capacity were significant and should be considered in transport capacity equations describing overland flow. Based on a series of flume experiments simulating typical overland flow, Everaert (1991) developed transport capacity relationships on slopes ranging from 1.7 to 17.4%, with and without rain on the surface.

Govers (1992) found that sediment transport capacity was linearly related to unit stream power when sediment size ranged from 58 to 218 μm and slope gradient was less than 17%. Hessel and Jetten (2007) evaluated the suitability of eight transport equations using data obtained from a small Loess Plateau catchment. They found that most equations were too sensitive to slope gradient and the transport rates were overpredicted for steep slopes. The Govers' equation performed best, mainly because of its low slope dependency, and was recommended to simulate sediment transport capacity by flowing water in conditions with small grain size and steep slopes. Guy *et al*. (2009b) reported that transport capacity of shallow overland flow was directly related to unit flow discharge (in excess of a threshold value) and slope, and inversely related to sediment density. The influence of sediment size in their study was insignificant, but the authors pointed out that it was probably caused by the relatively small size range examined. The sizes of test materials in their study ranged from 0.151 to 0.381 mm.

In the field, sediment sizes vary widely with soil type and aggregate size and stability. The size selectivity of overland flow (Poesen and Savat 1980, Ghadiri and Rose 1991, Farenhorst and Bryan 1995, Issa *et al*. 2006) indirectly indicates that the sediment transport capacity corresponding to a particular flow is strongly affected by sediment size. To date, the potential effects of sediment size on transport capacity of overland flow are not fully understood. Further studies are needed to quantify the relationships between sediment size and transport capacity of overland flow with a wide range of sediment size, particularly on steep slopes.

Hydraulic characteristics of overland flow and processes of sediment transport on steep slopes are different from those on gentle slopes (Nearing *et al*. 1999, Liu *et al*. 2000, Zhang *et al*. 2009). A recent study conducted by Zhang *et al*. (2009) showed that sediment transport capacity increased as a power function of flow discharge and slope gradient. Sediment transport capacity of overland flow was well simulated using shear stress and stream power parameters over a slope range of 8.8–46.6%. However, Zhang *et al*. (2009) only used mixed sediment with a median diameter of 280 μm. The effect of sediment size on transport capacity has not been evaluated on steep slopes. The objective of this study was to investigate the effects of sediment size on transport capacity of overland flow in a hydraulic flume over a wide range of flow discharge and slope gradient values.

MATERIALS AND METHODS

The experiments were conducted at the Fangshan station of Beijing Normal University. The hydraulic flume was 5 m long, 0.4 m wide with smooth glass walls and plexi-glass bed (Fig. 1). The bed slope of the flume could be adjusted manually from 0 to

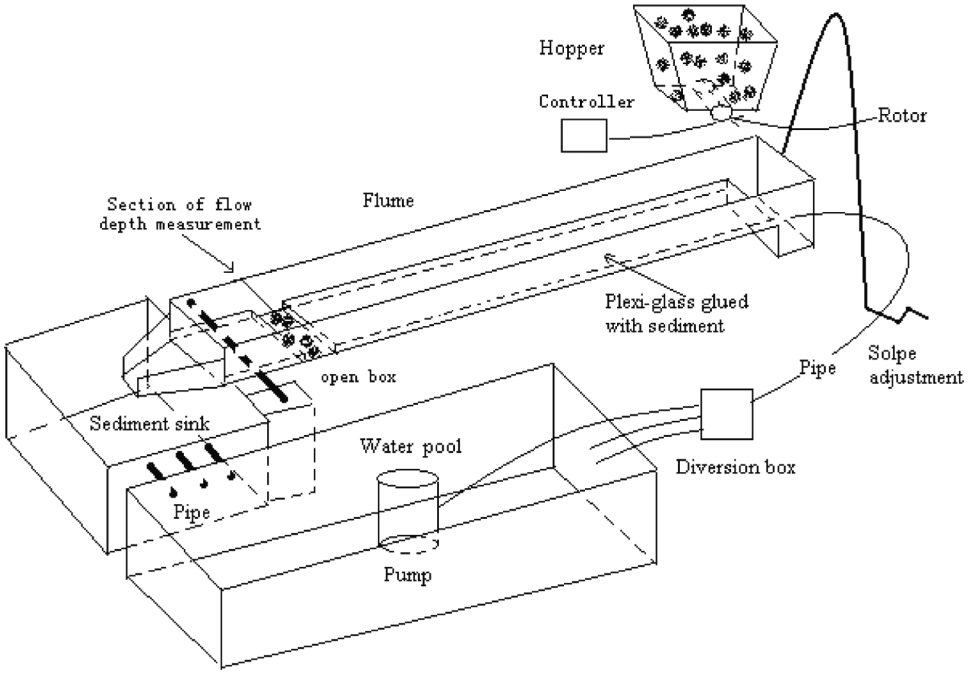

Fig. 1 Schematic diagram of experimental set-up.

60%. Sediment was collected from the bed of the Yongding River near Beijing. The sediment was air-dried and passed through a 2-mm sieve. A 5-mm layer of the sieved sediment (<2 mm) was glued on the flume bed to simulate grain roughness and remained constant during the experiments. To study the effect of sediment size on transport capacity of overland flow, the mixed sediment was further sieved into five classes: 0.02–0.15, 0.15–0.25, 0.25–0.59, 0.59–0.85 and 0.85–2.00 mm with d_{50} being 0.10, 0.22, 0.41, 0.69 and 1.16 mm, respectively. The size distributions of each sediment class along with the mixed sediment are given in Fig. 2. The sediment densities, measured by pyknometer method, were 2588, 2608, 2645, 2650 and 2650 kg m^{-3} for the five sediment classes, respectively.

Flow discharge was controlled by a series of valves installed on a flow diversion box. The flow discharge was collected at the lower end of flume with plastic buckets and measured with a volumetric cylinder. Flow discharge and slope gradient were adjusted to designated values before sediment introduction. After the flow became stable, flow depth was measured with a digital level probe (SX40-A, Chongqing Hydrological Equipment Factory) at the section of 0.6 m above the outlet. The resolution of the digital level probe was 0.01 mm and the accuracy was 0.04 mm. A previous test by measuring flow depth indicated that flows became steady before this section. Twelve flow depths were measured across the section. The maximum and minimum flow depths were eliminated from each set and the mean of the remaining 10 depths was taken as the average flow depth for that combination of flow discharge and slope gradient (Table 1). Mean flow velocity was calculated using the mean flow depth from the following simple volumetric relation (Table 1):

$$V = \frac{Q}{BH} \tag{1}$$

where Q is the flow discharge (m^3 s^{-1}); B is the width of the flume (m); and H is the measured mean flow depth (m). Mean values of flow depth and velocity were used to calculate flow shear stress, stream power, and unit stream power (Table 1) as follows:

$$\tau = \rho g H S \tag{2}$$

where τ is the shear stress (Pa); ρ is the water mass density (kg m^{-3}); g is the gravity constant (m s^{-2}); H is the mean flow depth (m); and S is the bed slope (m m^{-1}):

$$\omega = \tau V = \rho g S q \tag{3}$$

where ω is the stream power (kg m^{-3}); and V is the mean flow velocity (m s^{-1}):

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

where P is the unit stream power (m s^{-1}).

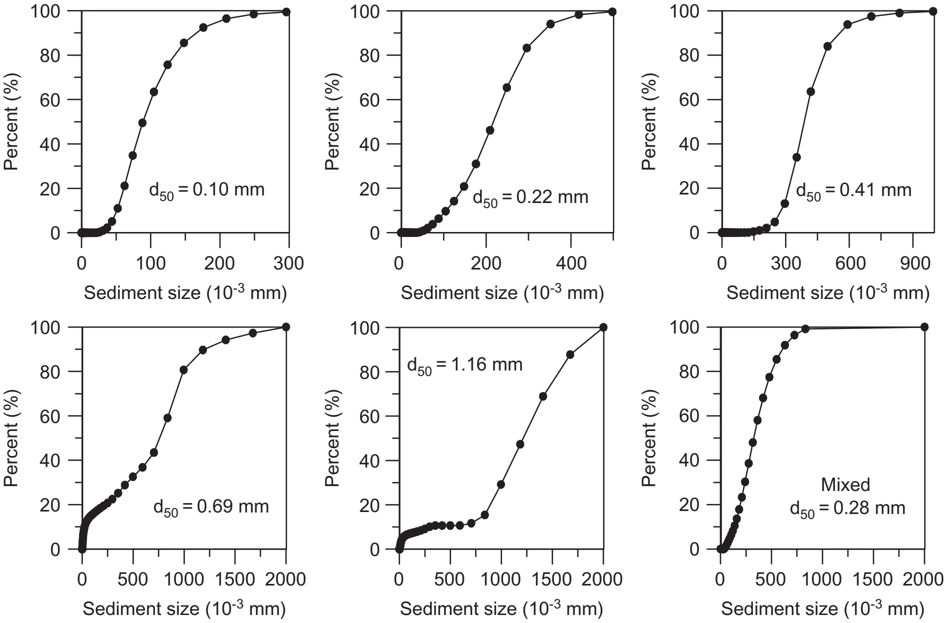

Fig. 2 Size distributions of five test sediment classes and mixed riverbed sediment.

Table 1 Measured flow depth, flow velocity, and computed shear stress, stream power, and unit stream power for 25 combinations of flow rate and slope gradient.

	Flow rate (10^{-3} m^2 s^{-1})	Slope gradient (%)				
		8.7	17.4	25.9	34.2	42.3
Flow depth (mm)	0.66	1.81	1.71	1.58	1.39	1.28
	1.32	2.87	2.76	2.24	2.11	1.86
	2.63	4.10	3.72	3.17	2.87	2.14
	3.95	5.11	4.53	3.99	3.87	3.59
	5.26	6.04	5.27	4.69	4.19	4.02
Flow velocity (m s^{-1})	0.66	0.36	0.39	0.42	0.48	0.51
	1.32	0.46	0.48	0.59	0.62	0.71
	2.63	0.64	0.71	0.83	0.92	1.23
	3.95	0.77	0.87	0.99	1.02	1.10
	5.26	0.87	1.00	1.12	1.26	1.31
Shear stres (Pa)	0.66	1.54	2.88	3.97	4.61	5.28
	1.32	2.41	4.63	5.61	6.99	7.63
	2.63	3.43	6.22	7.91	9.47	8.76
	3.95	4.25	7.53	9.90	12.72	14.60
	5.26	5.00	8.72	11.61	13.73	16.31
Stream power (kg m^{-3})	0.66	0.56	1.11	1.66	2.19	2.71
	1.32	1.07	2.21	3.30	4.36	5.40
	2.63	2.20	4.39	6.57	8.69	10.78
	3.95	3.28	6.56	9.81	12.97	16.05
	5.26	4.36	8.72	13.03	17.26	21.35
Unit stream power (m s^{-1})	0.66	0.03	0.07	0.11	0.16	0.22
	1.32	0.04	0.08	0.15	0.21	0.30
	2.63	0.06	0.12	0.22	0.31	0.52
	3.95	0.07	0.15	0.26	0.35	0.46
	5.26	0.08	0.17	0.29	0.43	0.55

Two sediment sources were designed to ensure that the sediment transport capacity was reached for each combination of flow discharge and slope gradient (Fig. 1). The first sediment source was a 1-m^3 hopper installed over the flume at a distance of 0.5 m from the upper end. The sediment feeding rate was controlled by the rotation speed of rotors installed within the hopper. The feeding rate from the hopper was adjusted at the beginning of each test and fixed during the test. The second sediment source was an open box (40 cm long, 20 cm wide, 5 cm deep) fitted across the flume bed at 0.5 m (the lower edge of the box) above the lower end of the flume. The box was filled flush with the flume bed with pre-wetted test sediment. During flow depth measurement the box was covered with a thin steel sheet coated (glued) with the mixed sediment that was pressed firmly against the flume bed to prevent erosion. After the flow depth measurement, sediment introduction was initiated. The sediment transport capacity measured by Zhang *et al*. (2009) was used as a guideline for adjusting sediment feeding rates. A steel rod was used to stir up deposits and set sediment in motion under the hopper during the test. The sediment feeding rate was increased gradually until the fed sediment could not be completely transported as indicated by deposition of sediment immediately downstream from the sediment feeder. The steel sheet was then removed, and transport capacity was measured. According to erosion theory, if transport capacity was not reached due to insufficient feeding from hopper, the deficit would be made up by sediment entrainment from the box to reach the sediment transport capacity. If severe erosion occurred in the box, the test was discarded.

Five samples were collected using plastic buckets for each test. The sampling period was recorded using a digital stopwatch and adjusted depending on flow rate (longer for small *Q* values and shorter for larger *Q* values) within the range of 5–20 s. The short sampling period for some treatments probably caused errors in transport capacity measurement. Generally, the test period lasted less than 5 min for each test. The collected samples were settled for 4 h, and the clear supernatant was decanted from the containers. The remaining wet sediment was oven dried at 105°C for 24 h. The dry sediment weight was divided by sampling time and the flume width to obtain sediment transport capacity. The average sediment load of the five samples was used as representative sediment

Table 2 Measured sediment transport capacities (kg m^{-1} s^{-1}) for five sediment sizes d_{50} (mm) under different combinations of flow rate and slope gradient.

	Flow rate(10^{-3} m^2 s^{-1})	Slope gradient (%)				
		8.7	17.4	25.9	34.2	42.3
$d_{50} = 0.10$	0.66	0.07	0.40	1.08	1.12	1.16
	1.32	0.33	0.63	1.31	2.52	2.55
	2.63	0.56	1.33	3.24	4.57	5.10
	3.95	1.44	2.91	4.48	6.20	7.10
	5.26	1.87	4.17	6.82	7.73	9.53
$d_{50} = 0.22$	0.66	0.06	0.19	0.65	0.78	0.99
	1.32	0.15	0.40	1.03	2.17	2.76
	2.63	0.48	1.15	3.08	4.49	5.11
	3.95	0.94	2.31	4.04	6.87	7.30
	5.26	1.03	3.90	6.64	7.11	8.66
$d_{50} = 0.41$	0.66	0.05	0.16	0.33	0.62	0.96
	1.32	0.14	0.37	0.88	1.22	2.73
	2.63	0.34	1.07	2.68	4.46	5.12
	3.95	0.53	1.46	3.04	6.06	6.83
	5.26	0.83	2.36	6.13	6.76	7.99
$d_{50} = 0.69$	0.66	0.05	0.16	0.21	0.46	0.67
	1.32	0.13	0.30	0.69	1.07	2.32
	2.63	0.31	0.83	1.83	3.22	4.20
	3.95	0.48	1.32	2.73	5.32	6.38
	5.26	0.70	2.03	5.65	6.40	7.58
$d_{50} = 1.16$	0.66	0.04	0.10	0.20	0.33	0.49
	1.32	0.13	0.28	0.48	0.91	1.84
	2.63	0.26	0.82	1.30	2.75	2.90
	3.95	0.44	1.01	2.49	4.80	5.65
	5.26	0.58	1.41	4.53	6.01	6.68

transport capacity for the given combination of flow discharge and slope gradient (Table 2).

The unit flow discharges were 0.66, 1.32, 2.63, 3.95 and 5.26 × 10^{-3} m^2 s^{-1}, and slope gradients were 8.7, 17.4, 25.9, 34.2 and 42.3%. Complete factorial combinations of five size classes × five slopes × five discharges were tested systematically by varying discharge, followed by slopes and then size classes. We experienced difficulty in feeding sufficient sediment from the hopper when T_c was extremely high at large discharges and steep slopes and especially for fine classes. In addition, fine sediment of the 0.1-mm class became sticky once mixed in water, which increased the difficulty of sediment introduction. Serious erosion occurred in the sediment box during the experiments in four cases having extremely high T_c. As a result, the three highest T_c measured for the 0.10-mm class and the maximum T_c measured at the greatest slope and discharge for the 0.22-mm class were discarded, and the remaining 121 T_c values were used in the analysis.

Relationships between sediment transport capacity and velocity, shear stress, stream power, or unit stream power for each size class were analysed by a simple regression method. The relationships between sediment transport capacity and sediment size and hydraulic variables were analysed by a multiple stepwise linear regression method. All analyses were conducted using the SPSS (Statistical Product and Service Solutions) software (version 11.5) at the 0.05 significance level.

RESULTS AND DISCUSSION

The measured sediment transport capacity decreased as sediment size increased (Table 2). The ratios of average transport capacity of the 0.10-mm class to those of other classes averaged 1.09, 1.30, 1.55 and 1.92 for the 0.22, 0.41, 0.69 and 1.16 mm classes, respectively. The capacity of the flow to transport sediment of different sizes increased as flow discharge and slope gradient increased. For each size class tested, sediment transport capacity could be estimated as a power function of unit flow discharge and slope gradient with the coefficient of determination exceeding 0.95 (Table 3). The exponent of the unit flow discharge increased from 1.17 to 1.33 as sediment size increased from 0.10 to 1.16 mm. Both the coefficient and exponent of slope gradient showed an increasing trend with sediment size; however, the trend

Table 3 Transport capacity (T_c) as a power function of flow discharge (q) and slope gradient (S) for five sediment sizes.

Sediment sizes (mm)	Function	R^2	n
0.10	$T_c = 22594.36q^{1.168}S^{1.446}$	0.95	22
0.22	$T_c = 45919.80q^{1.270}S^{1.666}$	0.98	24
0.41	$T_c = 34593.94q^{1.243}S^{1.732}$	0.99	25
0.69	$T_c = 36643.76q^{1.295}S^{1.673}$	0.99	25
1.16	$T_c = 35399.73q^{1.333}S^{1.622}$	0.99	25

was not consistent for all sediment sizes. This result agreed with the conclusion of Guy *et al.* (2009b) that transport capacity of overland flow could be estimated by a power function of flow rate and slope gradient. However, the best fitted exponents of flow discharge and slope gradient were less than the values reported by Guy *et al.* (2009b). In their study, the mean diameter of medium and fine sands was approximately 0.21 mm, and the mean regression exponents of discharge and slope gradient were 1.39 and 2.36, respectively. In comparison, the corresponding values for the 0.22 mm class in this study were only 1.27 and 1.67 (Table 3). The differences were probably caused by differences in slope gradients. The slope gradients ranged from 1 to 12% in the study of Guy *et al.* (2009b), while they varied from 8.7 to 42.3% in this study. In addition, there was slight difference in treatment of the surface grain roughness in the two studies, but it should not cause such a big difference in the fitted parameters. The test materials were glued onto the flume bed in their study, while a 5-mm layer of the mixed sediment was used in this study. However, the median diameter of the mixed sediment was 0.28 mm, which was pretty close to the median diameter of 0.22 mm for the size class discussed above.

A multiple stepwise linear regression indicated that sediment transport capacity could be estimated using a power function of flow discharge, slope gradient, and sediment size for the pooled data set:

$$T_c = 2382.32q^{1.269}S^{1.637}d_{50}^{-0.345} \qquad (R^2 = 0.98; n = 121) \tag{5}$$

where T_c is the sediment transport capacity (kg m^{-1} s^{-1}); q is the unit flow discharge (m^2 s^{-1}); S is the slope gradient (m m^{-1}); and d_{50} is the median diameter of sediment (m). Equation (5) simulated measured transport capacity adequately with a coefficient of determination of 0.98 (Fig. 3). The relative error ranged from −47.1 to 46.5%, with a mean value of 1.4%. However, the model overpredicted transport capacities when sediment transport capacity was greater than 7 kg m^{-1} s^{-1}, indicating a predictive limitation with the model. A similar overprediction for $T_c > 7$ kg m^{-1} s^{-1} was also reported in a previous study using the mixed sediment (Zhang *et al.* 2009). This consistent overprediction further revealed that there was a limitation with this type of regression models for predicting T_c.

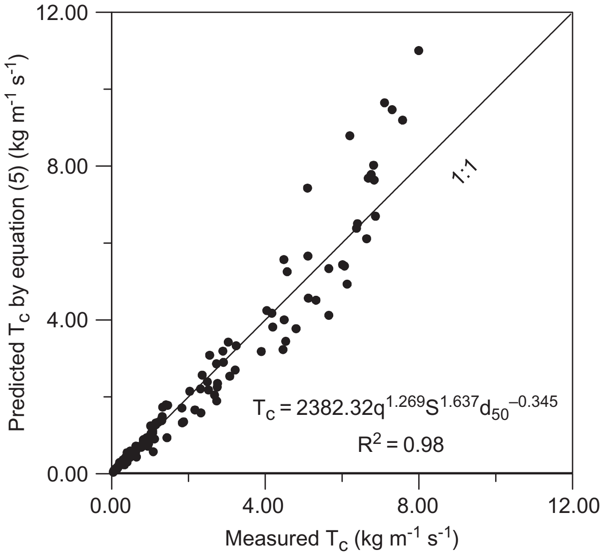

Fig. 3 Measured *vs* calculated sediment transport capacity using equation (5).

Generally, simulated absolute errors increased as measured transport capacity increased, especially when measured transport capacity was greater than 7 kg m^{-1} s^{-1} (Fig. 4). Although this trend is consistent with the common knowledge that absolute errors often increase with mean values, increased variability in flow hydraulics and increased difficulty in measuring T_c for flow with great sediment concentration might have played a certain role. The flow regime, viscosity, discharge, depth, velocity, and friction coefficient of sediment-laden overland flow changed as sediment load increased (Li and Abrahams 1997, Abrahams and Li 1998, Summer and Zhang 1998). A recent study conducted by Zhang *et al.* (2010) on steep slopes (8.7–34.2%) using the same flume showed that hydraulics of sediment-laden overland flow were significantly affected by sediment load. Compared to the clear water, the average decreases in Reynolds number and Froude number of sediment laden flow were 23.0 and 24.1% as sediment load increased from 0.017 to 6.95 kg m^{-1} s^{-1}. The mean flow velocity decreased as sediment load increased

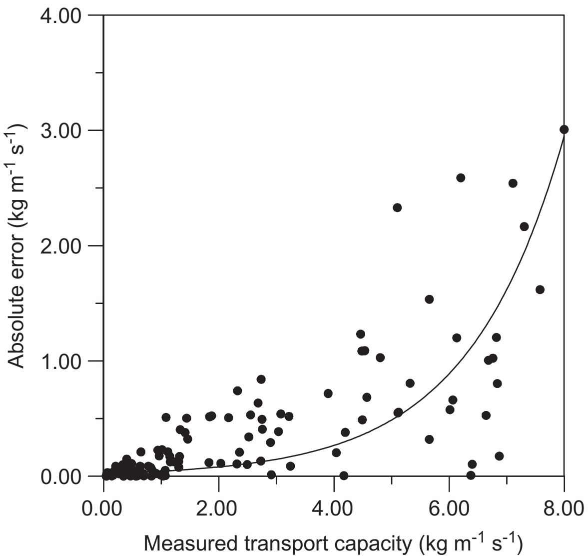

Fig. 4 Absolute error simulated using equation (5) as a function of measured transport capacity.

up to 0.071 m s^{-1}. The Darcy-Weisbach friction coefficient increased with sediment load, showing that the total energy consumption increased with sediment load. The effects of sediment load on friction coefficient depended on flow discharge. As flow discharge increased, the influence of sediment load on friction coefficient decreased due to increased flow depth and reduced relative roughness. The decreases in flow turbulence and flow velocity caused by increases in flow viscosity and friction certainly influenced the measured transport capacity. The compounded effects of sediment load on flow hydraulics might have increased variability in T_c measurements.

Zhang *et al*. (2009) showed that mean flow velocity was closely related to sediment transport capacity of overland flow on steep slopes. A critical or threshold velocity existed for sediment transport by overland flow. The regression relationships between the mean flow velocity and sediment transport capacity for different sediment sizes are given in Table 4. Sediment transport capacity increased linearly with mean flow velocity. The regression coefficients decreased as sediment size increased except for the finest class. The threshold velocity (V_{thr}) calculated as a ratio of the regression coefficient to constant (Table 4) increased as a power function of sediment size from 0.378 to 0.482 m s^{-1} (Fig. 5).

Table 4 Linear regression between transport capacity and mean flow velocity for different sediment sizes. Threshold velocity (V_{thr}) was a ratio of the regression constant to coefficient.

Sediment sizes (mm)	Function	V_{thr} (m s^{-1})	R^2	*n*
0.10	$T_c = 7.034V - 2.661$	0.378	0.81	22
0.22	$T_c = 7.935V - 3.412$	0.430	0.80	24
0.41	$T_c = 7.758V - 3.570$	0.460	0.79	25
0.69	$T_c = 7.108V - 3.385$	0.476	0.78	25
1.16	$T_c = 6.117V - 2.948$	0.482	0.74	25

$$V_{\text{thr}} = 0.976 d_{50}^{0.100} \quad (R^2 = 0.93) \qquad (6)$$

This result implied that the minimum velocity or energy needed to transport sediment was dependent on sediment size. The larger the sediment size the more energy was needed for setting sediment in motion. Shields (1936) found that incipient motion of river bed particles was closely related to slope gradient. Guy *et al*. (2009b) reported that a threshold flow discharge existed for sediment transport, which was a power function of sediment size and slope gradient. The threshold discharge decreased with slope gradient. However, in this study the calculated threshold velocity was independent of slope gradient. It was probably caused by the range of slope gradient evaluated in this study, because the transport threshold could usually be neglected in transport capacity equations on steep slopes (Hessel and Jetten 2007).

Many studies indicated that sediment transport capacity could be simulated well by shear stress of flow (Yalin 1963, Finkner *et al*. 1989, Zhang *et al*. 2008, 2009). The relationships between shear stress and transport capacity of different sediment sizes were analysed (Table 5). For each size class, transport capacity was closely related to shear stress with

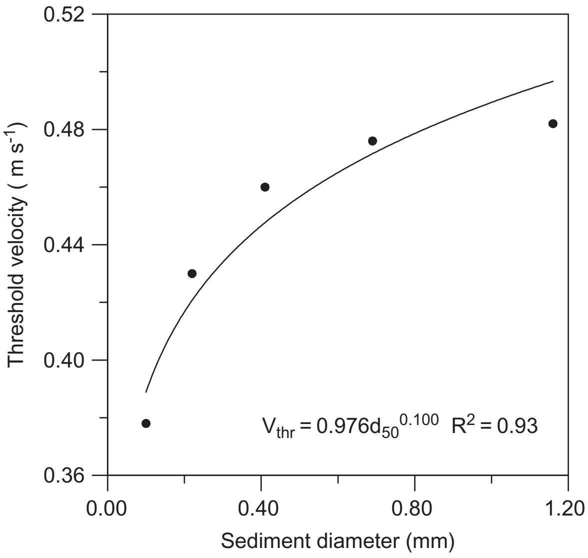

Fig. 5 Calculated threshold velocity as a function of sediment size.

Table 5 Transport capacity as a power function of shear stress (τ) for different sediment sizes.

Sediment sizes (mm)	Function	R^2	*n*
0.10	$T_c = 0.044\tau^{2.065}$	0.95	22
0.22	$T_c = 0.022\tau^{2.294}$	0.97	24
0.41	$T_c = 0.018\tau^{2.309}$	0.97	25
0.69	$T_c = 0.015\tau^{2.314}$	0.97	25
1.16	$T_c = 0.012\tau^{2.320}$	0.97	25

Table 7 Transport capacity as a power function of unit stream power (P) for different sediment sizes.

Sediment size (mm)	Function	R^2	*n*
0.10	$T_c = 20.648P^{1.317}$	0.76	22
0.22	$T_c = 25.893P^{1.555}$	0.85	24
0.41	$T_c = 23.388P^{1.615}$	0.89	25
0.69	$T_c = 19.231P^{1.601}$	0.87	25
1.16	$T_c = 15.311P^{1.581}$	0.84	25

a coefficient of determination greater than 0.95. The exponent of shear stress increased with sediment size. The coefficients in the regression models decreased from 0.044 to 0.012 as sediment size increased. In a similar study using the same flume but the mixed sediment (sieved to <2 mm with a d_{50} of 0.28 mm), Zhang *et al*. (2009) reported that the best fitted exponent and coefficient were 1.982 and 0.054, respectively, which were closer to those of the finest class ($d_{50} = 0.10$ mm) than to those of the second finest class having a similar d_{50} of 0.22 mm. The discrepancy further revealed the effect of sediment size on transport capacity, stemming from complex interactions between size classes. Interaction of transport capacity among different particle sizes is complex for mixed sediment. There is no widely accepted method of computing composite T_c for mixed sediment transport. The effect of sediment size distribution on composite T_c on steep slopes should be an interesting research topic in future studies.

The relationships between sediment transport capacity and stream power for the different sediment sizes were shown in Table 6. For all sediment sizes sediment transport capacity increased as a power function of stream power. The coefficients of determination for all size classes were greater than 0.94. The regression coefficients decreased from 0.283 to 0.095 as the median sediment size increased from 0.10 to 1.16 mm, while the exponents of stream power increased from 1.266 to 1.441.

Table 6 Transport capacity as a power function of stream power (ω) for different sediment sizes.

Sediment diameters (mm)	Function	R^2	*n*
0.10	$T_c = 0.283\omega^{1.266}$	0.94	22
0.22	$T_c = 0.178\omega^{1.413}$	0.96	24
0.41	$T_c = 0.141\omega^{1.423}$	0.96	25
0.69	$T_c = 0.117\omega^{1.435}$	0.97	25
1.16	$T_c = 0.095\omega^{1.441}$	0.96	25

The use of unit stream power for predicting sediment transport capacity of overland flow on steep slopes was questioned by Zhang *et al*. (2009), and was also evaluated here (Table 7). For all sediment size classes, transport capacity increased as a power function of unit stream power. The coefficients of determination ranged from 0.76 to 0.89, i.e. they were much lower than those of shear stress and stream power. This result is consistent with the findings reported by Zhang *et al*. (2009).

It should be pointed out that the feedback effects of sediment load on flow hydraulics were not included in this study. The flow depth, mean velocity, and related hydraulic parameters such as shear stress, stream power, and unit stream power for a given discharge and slope were determined using clear water without sediment. The best fitting equations developed using clear water hydraulics may likely overestimate transport capacity for sediment-laden flows if hydraulics of sediment-laden flow is used in the equations. Another potential issue is that a 5-mm layer of mixed sediment ($d_{50} = 0.28$ mm, Fig. 2) was glued to the flume bed and used for all size classes. The grain roughness from the mixed sediment would be "rougher" for fine classes and "smoother" for coarse classes. Theoretically, the rougher surface for the finest size class would impede sediment movement, and thus result in under-estimation of transport capacity. In contrast, the smoother roughness would result in over-estimation of transport capacity. To avoid this shortcoming the same materials as the test sediment should be glued on the flume bed.

The median diameter of sediment used in this study varied from 0.1 to 1.16 mm. In field conditions, most eroded soil particles were smaller than 0.1 mm (Poesen and Savat 1980, Issa *et al*. 2006). Further studies with fine soil particles and aggregated soils are needed to quantify the effects of sediment size on transport capacity of overland flow on steep slopes. The potential effects of sediment load on flow hydraulics also need to be included.

SUMMARY AND CONCLUSIONS

This study was conducted to investigate the effects of sediment size on transport capacity of overland flow on steep slopes. The results showed that sediment size was inversely related to sediment transport capacity. The ratios of average transport capacity of the finest sediment (0.10 mm) to those of the other sediment sizes were 1.09, 1.30, 1.55 and 1.92 for the 0.22, 0.41, 0.69 and 1.16 mm classes, respectively. The effects of sediment size on transport capacity should be included in sediment transport capacity equations for overland flow on steep slopes. Sediment transport capacity for all size classes increased as a power function of flow discharge and slope gradient, shear stress, stream power, or unit stream power. Transport capacity generally decreased with sediment size to a power of −0.35. The results corroborated the conclusion of Zhang *et al*. (2009) that shear stress and stream power were better hydraulic variables than unit stream power to simulate transport capacity on steep slopes. Sediment transport capacity increased linearly with mean flow velocity. The threshold velocity increased as a power function with sediment size. Overall results showed that all the formulations have drawbacks for estimating sediment transport capacity on steep slopes, especially when T_c is greater than 7.0 kg m^{-1} s^{-1}. Compensatory interactions between particle size classes should be considered when computing composite transport capacity for mixed sediment. Further studies with fine soil particles are needed to quantify the effects of sediment size and aggregates on transport capacity on steep slopes.

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