Hydrol. Earth Syst. Sci. Discuss., 8, 6939–6965, 2011
www.hydrol-earth-syst-sci-discuss.net/8/6939/2011/
doi:10.5194/hessd-8-6939-2011

Hydrology and Earth System Sciences Discussions

Effect of hydraulic parameters on sediment transport capacity in overland flow over erodible beds

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Received: 21 June 2011 – Accepted: 12 July 2011 – Published: 14 July 2011

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Sediment transport is an important component of the soil erosion process, which depends on several hydraulic parameters like unit discharge, mean flow velocity, and slope gradient. In most of the previous studies, the impact of these hydraulic parameters on transport capacity was studied for non-erodible bed conditions. Hence, this study aimed to examine the influence of unit discharge, mean flow velocity and slope gradient on sediment transport capacity for erodible beds and also to investigate the relationship between transport capacity and composite force predictors i.e. shear stress, stream power, unit stream power and effective stream power. In order to accomplish the objectives, experiments were carried out using four well sorted sands (0.230, 0.536, 0.719, 1.022 mm). Unit discharges ranging from 0.07 to 2.07 × 10^{-3} m^2 s^{-1} were simulated inside the flume at four slopes (5.2, 8.7, 13.2 and 17.6 %) to analyze their impact on sediment transport rate. The sediment transport rate measured at the bottom end of the flume by taking water and sediment samples was considered equal to sediment transport capacity, because the selected flume length of 3.0 m was found sufficient to reach the transport capacity. The experimental result reveals that the slope gradient has a stronger impact on transport capacity than unit discharge and mean flow velocity due to the fact that the tangential component of gravity force increases with slope gradient. Our results show that unit stream power is an optimal composite force predictor for estimating transport capacity. Stream power and effective stream power can also be successfully related to the transport capacity, however the relations are strongly dependent on grain size. Shear stress showed poor performance, because part of shear stress is dissipated by bed irregularities, bed form evolution and sediment detachment. An empirical transport capacity equation was derived, which illustrates that transport capacity can be predicted from median grain size, total discharge and slope gradient.

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1 Introduction

Soil erosion has become a major global environmental problem (Lal, 1998). Several physically based soil erosion models have been developed to estimate sediment yield at the catchment scale (KINEROS2, Smith et al., 1995; LISEM, De Roo et al., 1996; EUROSEM; Morgan et al., 1998; WEPP, Flanagan et al., 2001). Soil erosion is a combination of detachment and transport of sediment particles. An accurate estimation of these processes is the main objective of a physically based model. Most of the existing models estimate sediment detachment by using the concept of Foster and Meyer (1972). According to this concept, the detachment rate of flowing water is calculated as the difference between the sediment transport capacity and actual sediment load. Hence, sediment transport capacity plays a pivotal role in the physical description of soil erosion processes.

Sediment transport capacity is defined as the maximum sediment load that a particular discharge can transport at a certain slope (Merten et al., 2001). During the last three decades, several efforts have been made to analyze the influence of different hydraulic parameters on transport capacity, such as unit discharge, mean flow velocity, and slope gradient (Beasley and Huggins, 1982; Julien and Simons, 1985; Govers and Rauws, 1986; Finkner et al., 1989; Govers, 1990; Guy et al., 1990: Everaert, 1991; Govers, 1992; Abrahams and Li, 1998; Jayawardena and Bhuiyan, 1999; Prosser and Rustomji, 2000; Abrahams et al., 2001; Zhang et al., 2009). The influence of these hydraulic parameters has mainly been studied using datasets obtained from flume experiments, which had non-erodible beds. For erodible bed experiments, previous researchers usually assumed that their selected flume length was adequate to reach the transport capacity (e.g. Govers, 1990; Everaert, 1991). But, qualitative and quantitative information about the spatial variation in sediment load is needed to verify this assumption.

The relationship between transport capacity and unit discharge has often been studied, and previous research has made it clear that this relationship is always dependent on slope (Beasley and Huggins, 1982; Julien and Simons, 1985; Govers and Rauws, 1986; Govers, 1990; Everaert, 1991; Jayawardena and Bhuiyan, 1999; Prosser and Rustomji, 2000; Lei et al., 2001; Zhang et al., 2009). However, the effect of unit discharge and slope on transport capacity varies from erodible to non-erodible bed conditions (Gover, 1990; Everaert, 1991; Zhang et al., 2009), probably due to the fact that, for the same hydraulic and sediment conditions the roughness of erodible beds is always higher than that of non-erodible beds (Hu and Abrahams, 2006). Govers (1990) and Everaert (1991) found, in different studies, that for erodible beds the effect of slope on transport capacity is higher than the effect of unit discharge. However, the non-erodible bed experiments of Zhang et al. (2009) revealed that transport capacity is more susceptible to unit discharge as compared to slope, contradicting the previously mentioned results. This raises questions about the applicability of information obtained from non-erodible beds for the development of sediment transport equations to be used in soil erosion models.

The influence of mean flow velocity on transport capacity has been studied mainly under non-erodible bed conditions (Guy et al., 1990; Abrahams and Li, 1998; Zhang et al., 2009, 2010a, b). Guy et al. (1990) found that transport capacity increases as mean flow velocity increases, because mean flow velocity consistently increases with slope. Zhang et al. (2009) even reported a linear increase of transport capacity with increasing mean flow velocity for non-erodible beds. Again, contradicting results were found under erodible bed conditions (Govers, 1990; Nearing et al., 1997; Takken et al., 1998; Nearing et al., 1999; Gimenez and Govers, 2001), where the influence of slope on flow velocity was non-significant and, consequently, flow velocity had no clear influence on sediment transport capacity. As a result, it is clear that there is a need to comprehensively study the influence of different hydraulic parameters on sediment transport capacity.

Several scientists have used composite force predictors to estimate transport capacity of overland flow (Yang, 1972; Moore and Burch, 1986; Govers and Rauws; 1986; Lu et al., 1989; Govers, 1990; Everaert, 1991; Govers, 1992; Jayawardena and Bhuiyan, 1999; Prosser and Rustomji, 2000; Abrahams et al., 2001; Zhang et al.,

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2009). Hydraulic variables were combined in different ways to form composite force predictors for the estimation of transport capacity i.e. shear stress, stream power, unit stream power, and effective stream power (Duboys, 1879; Bagnold, 1966; Yang, 1972; Govers, 1990). But widely varying results were obtained, because the performance of composite force predictors were tested under different ranges of morphologic conditions. Govers and Rauws (1986) concluded that shear stress is not a good predictor for estimating transport capacity under erodible bed conditions, because an important component of the shear stress (i.e. form shear stress) may not be actively used for sediment transport, but could be preferentially consumed on sediment detachment and bed form evolution. Therefore, they suggested the use of grain shear stress (the part of shear stress consumed on individual grains) and unit stream power concepts to predict transport capacity on erodible beds. However, later results from Govers (1990) contradict the recommendations of Govers and Rauws (1986), showing that shear stress can be used to estimate transport capacity under erodible beds. In addition, the experimental results of Zhang et al. (2009) also depicted that transport capacity was well predicted by shear stress for non-erodible bed conditions.

The influence of unit discharge and mean flow velocity on transport capacity under erodible bed conditions is still ambiguous, and needs to be further examined, in order to get a better understanding of the processes involved in sediment transport by overland flow. In addition, the selection of a suitable composite predictor for the estimation of transport capacity is also still uncertain. Therefore, the objectives of this research were (i) to study the effect of unit discharge, mean flow velocity and slope gradient on sediment transport capacity and how these relations vary in the presence and absence of bed irregularities, and (ii) to evaluate the potential of different composite force predictors for the estimation of transport capacity under overland flow conditions. Fundamental for addressing these objectives is knowing if the selected experimental setup is sufficient for reaching the transport capacity. To tackle these objectives, an experiment on erodible beds was designed with variable slopes, discharges and grain sizes.

2 Materials and methods

For this study, a 3.0 m long and 0.5 m wide rectangular flume with a wooden floor and one sided plexiglass wall was constructed. The experimental set-up was similar to the one described by Ali et al. (2011). In order to abridge the edge effects, a piece of wood (length = 0.20, width = 0.50, height = 0.04 m, "stopper") was fixed at the upper end of the flume and a second stopper (length = 0.10, width = 0.50, height = 0.04 m) was fixed at the lower end (Fig. 1). The upper stopper also allows the water to enter into the test section from the head tank avoiding erosion and causing uniform spread of the applied discharge across the flume width. The length of the lower stopper (i.e. 0.10 m) was selected to allow passing of the water and sediment mixture without causing any serious deposition. Tap water was used to conduct the experiments, which entered into the flume from a head tank. The rate of flow into the head tank was controlled by a valve and measured with a calibrated flow-meter at the inlet pipe. The flow-meter was connected to a data-logger and computer for continuous monitoring of the inflow rate. The applied unit discharge rates ranged from 0.07 to 2.07×10^{-3} m^2 s^{-1}.

In order to study the variation of sediment transport capacity with grain size, four well sorted non-cohesive medium to very coarse sands with median grain size (D_{50}) equal to 0.233, 0.536, 0.719, and 1.022 mm and with a bulk density of 1600 kg m^{-3} were used. Prior to each experiment, the test section was filled with a 0.04 m thick layer of sediment and saturated with water. The contact area between the upper stopper and sand layer was covered with a piece of artificial grass carpet, in order to dissipate the flow energy of the inflowing water. However, sudden high rates of erosion could not be fully prevented. For the experiments, the flume bed was adjusted to four slope gradients (5.2, 8.7, 13.2 and 17.6 %), to analyze the impact of slope on sediment transport capacity. Before each experiment, test runs were carried out to adjust the duration of the inflow for each combination of applied unit discharge, slope gradient and sediment type. As a result of these test runs, the time to conduct experiments ranged between 5 and 30 min. Each experimental run was repeated once to ensure the results.

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As flow depths are usually hard to assess under overland flow conditions on a changing bed due to the unsteadiness of the water and bed surface, two point gauges with an accuracy of 0.1 mm were hung on a wooden frame above the lower stopper of the flume, directly downstream of the sand bed. The mean flow depth was calculated by taking the average of the measurements taken from both gauges.

Mean flow velocity is difficult to measure under interrill and rill erosion due to spatial variation of bed geometry and limited flow depth (Jayawardena and Bhuiyan, 1999). The conversion of surface flow velocity measurements into mean flow velocity has also become a challenge, because of the selection of a suitable correction factor (Dunkerley, 2001). Hence in this study, mean flow velocities were estimated using the equation derived by Ali et al. (2011) for the same flume:

$$\mathrm{Log}(U) = 0.645 + 0.506\mathrm{Log}(Q) - 0.172\mathrm{Log}(D_{50}) \quad (1)$$

Where U (m s^{-1}) is the mean flow velocity, Q (m^3 s^{-1}) is the total discharge, and D_{50} (m) is the median grain diameter of the bed material.

During each run, a mixture of water and sediment was collected in a container at the bottom end of the flume at regular time intervals (1–5 min). Five to six samples were taken during each run, depending on the duration of the run. Supernatant water was poured out from the sample when the sediment settled down on the bed of the container. The remaining wet sediment was oven dried at 105 °C for 12 h, then weighed to determine the dry sediment weight. Average dry sediment weight was calculated by taking the mean dry weight of all sediment samples taken during each run. The sediment transport rate was determined by dividing the average dry sediment weight with run duration and flume width (i.e. 0.50 m).

In order to quantify the sediment budget along the flume length, the bed of the flume was scanned with a surface laser scanner for a selected number (45) of runs, before and after overland flow simulation. The elevation accuracy of the scanner is 1.0 mm. Using the data obtained from the laser scanner, detailed topographic maps with a horizontal spatial resolution of 5.0 mm were constructed using the triangulation method

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in the SURFER software package (Golden Software, 2004). Starting at 0.74 m below the upper stopper, 2.0 m of the flume length were scanned. The scanned area of the flume was divided into twenty equivalent slices of 100.0 mm length to study the sediment budget along the flume length. For each slice, the weight of the eroded sediment was calculated dividing eroded sediment volume by bulk density (i.e. 1600 $kg\,m^{-3}$). The calculated weight of the eroded sediment was further divided by duration of an experiment and area of a slice (i.e. 500 cm^2) to estimate the sediment detachment or deposition rate along the flume length. This was done after each 100.0 mm interval for each combination of discharge, slope, and grain size.

The calculated sediment budget along the flume length was used to corroborate the hypothesis that a flume length of 3.0 m is adequate to reach the transport capacity for the given conditions of flow, slope and sediment type, for which the experiments were conducted. The effects of unit discharge, mean flow velocity and slope gradient on transport capacity were analyzed graphically.

Prediction of sediment transport capacity was done by regression analysis in order to identify an optimal predictor among shear stress, stream power, unit stream power and effective stream power. Shear stress is defined as the force applied by flowing water on the soil surface per unit bed area (Duboys, 1879):

$$\tau = \rho u_*^2 \tag{2}$$

Where τ ($N\,m^{-2}$) is the shear stress, ρ ($kg\,m^{-3}$) is the density of water, $u_* = \sqrt{gRS}$ ($m\,s^{-1}$) is the shear velocity, g ($m\,s^{-2}$) is the gravitational acceleration, R (m) is the hydraulic radius, which is considered equal to the flow depth (h) under overland flow conditions, and S ($m\,m^{-1}$) is the slope gradient. The stream power concept was introduced by Bagnold (1966) who assumed that the sediment transport rate is a function of time rate of potential energy expenditure per unit bed area:

$$\varpi = \tau U \tag{3}$$

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Where ω ($\mathrm{J\,m^{-2}\,s^{-1}}$) is the stream power, and U ($\mathrm{m\,s^{-1}}$) is the mean flow velocity. Yang (1972) assumed that the sediment transport rate is a function of time rate of potential energy expenditure per unit weight of water:

$$\omega_u = US \tag{4}$$

Where ω_u ($\mathrm{m\ s^{-1}}$) is the unit stream power. Effective stream power is fundamentally based on the shear stress concept (Govers, 1990):

$$\omega_{\mathrm{eff}} = \frac{(\tau U)^{1.5}}{h^{0.67}} \tag{5}$$

Where ω_{eff} ($\mathrm{N^{1.5}\,s^{-1.5}\,m^{-2.17}}$) is the effective stream power.

3 Results and discussion

The measured sediment transport capacities for the selected sands, slope gradients, and unit discharges are given in Table 1. The transport capacities of the four sands varied from 0.0008 to 0.1337 $\mathrm{kg\,m^{-1}\ s^{-1}}$ (Table 1), and are in approximately the same range as measured by Govers (1990) and Everaert (1991) for similar ranges of hydraulic and sediment conditions. During our experiment, the calculated values of the Reynolds number ranged from 253 to 7916, and the Froude number ranged from 0.7 to 2.3, which implies that the flow conditions inside the flume ranged from laminar to turbulent and from subcritical to supercritical, respectively.

3.1 Sediment budget along the flume length

Figure 2 shows the variation in sediment budget along the flume length for the three unit discharges (0.17, 0.33 and 0.50 × $10^{-3}\ \mathrm{m^2\ s^{-1}}$) at a slope of 13.2 % for four sands. These were calculated from the laser scanner data. It is clear that the detachment rate is at a maximum level at the upper side of the flume where clean water enters and

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decreases with distance for each of the three applied unit discharges. This is due to the fact that the flow energy, which is required to detach sediment particles from the soil mass, decreases with the increase of sediment load (Lei et al., 1998; Merten et al., 2001). On the other hand, deposition rate increases progressively along the flume length. After a certain distance, the system attained an equilibrium between sediment detachment and deposition, so the net detachment became zero and sediment load achieved its steady (maximum) value (Fig. 2a, b and c). According to Foster and Meyer (1972), the sediment rate reaches its maximum (= transport capacity), when the detachment rate becomes zero. Therefore, the steady value of sediment load for a particular discharge and slope corresponded to the sediment transport capacity of the flowing water. Similar results were obtained from the other runs, which were carried out at 5.2, 8.7 and 17.6 % slopes. Thus, the flume length of 3.0 m was found sufficient to reach the sediment transport capacity. As a result, the average sediment transport rate measured at the bottom end of the flume by taking samples of water and sediment mixture during each experimental run was assumed to represent the sediment transport capacity.

3.2 Effect of unit flow rate and mean flow velocity on sediment transport capacity

As shown in Fig. 3, the measured transport capacity increased with unit discharge. Moreover, slope also had a strong influence on the measured transport capacity. For instance, when simulating a unit discharge of 0.33×10^{-3} $m^2\,s^{-1}$, the measured value for transport capacity at a slope of 5.2 % was 94 % lower than the value obtained at a 17.6 % slope (Fig. 3). The strong impact of slope on transport capacity can be explained by the generally known phenomenon that the tangential component of gravity force, which acts along the bed in a downstream direction, increases with slope (Chorley et al., 1984). This is likely to be the reason that the measured transport capacity was more sensitive to slope than to unit discharge for erodible beds. These results agree with others' findings (Beasley and Huggins, 1982; Govers and Rauws, 1986; Govers,

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1990; Everaert, 1991), but contradict the results of Guy et al. (1987) and Zhang et al. (2009). The latter studies, conducted on fixed beds, ignored the dynamics of knick-points, headcuts, scour hole, slumping of the rill walls, etc. as well as the variation in bed form, where unit discharge has more strong impact on transport capacity as compared to slope.

Under non-erodible beds, sediment transport capacity is anticipated to be over-predicted because (i) the available flow energy is preferentially used for sediment transport, but any excess energy could lead to the detachment of deposited sediment, and (ii) the resistance of non-erodible beds is noticeably less than those of erodible beds (Gimenez and Govers, 2001; Hu and Abrahams, 2006; Zhang et al., 2010c). With erodible beds on the other hand, irregularities increase with slope and slow down the water flow by reducing the local slope, whereby the transport capacity is reduced (Gimenez and Govers, 2001, 2002). The available flow energy under erodible bed conditions is not only used for transport of sediment, but is also greatly dissipated by the bed irregularities as well as the detachment of sediment (Gimenez and Govers, 2001, 2002).

Mean flow velocity is another important hydraulic parameter affecting sediment transport capacity, and depends on total discharge, median grain size, and bed geometry (Ali et al., 2011). Figure 4 shows that the transport capacity increased with the increase of mean flow velocity for each slope class. Again it is clearly illustrated that slope had a pronounced effect on the correlations between transport capacity and mean flow velocity. Experimental results revealed that transport capacity substantially increased with slope at a fixed mean flow velocity value (Fig. 4). For example at a mean flow velocity of $0.18\,\mathrm{m\,s^{-1}}$, the measured values of transport capacity were $0.003\,\mathrm{kg\,m^{-1}\,s^{-1}}$ at 5.2 % slope, and $0.095\,\mathrm{kg\,m^{-1}\,s^{-1}}$ at 17.6 % slope, respectively (Fig. 4). This is due to the fact that the flow energy of a particular discharge substantially increases with slope, but a major part of the flow energy is dissipated for the detachment and transport of sediment instead of increasing flow velocity (Gimenez and Govers, 2002). However, Guy et al. (1990) and Zhang et al. (2009) found that the relationship between

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transport capacity and mean flow velocity was almost independent of slope. The possible reason for this contradiction is that under non-erodible beds the mean flow velocity gradually increases with slope due to less variation in bed roughness (Foster et al., 1984; Abrahams et al., 1996; Gimenez and Govers, 2001; Zhang et al., 2009), while for erodible beds the mean flow velocity is almost independent of slope effect because bed morphology and roughness is dependent on both discharge and slope (Govers 1992; Nearing et al., 1997; Takken et al., 1998; Nearing et al., 1999; Gimenez and Govers, 2001). Therefore, the theoretical concepts derived from non-erodible beds do not necessarily reflect erodible bed conditions, and their application on a natural hillslope may produce errors.

3.3 Prediction of sediment transport capacity

In previous studies composite force predictors have often been correlated with sediment transport capacity and most of the time it has been found that the relationship between transport capacity and a composite predictor can vary with grain size (Govers and Rauws, 1986; Govers, 1990; Everaert, 1991; Abrahams et al., 1998; Ferro, 1998; Jayawardena and Bhuiyan, 1999; Zhang et al., 2009). Because in this study four types of sand were used to conduct the experiments, it is expected that grain size also significantly affects the relationships between transport capacity and composite force predictors.

Sediment transport capacity was modelled as a power function of composite force predictors i.e. shear stress, stream power, unit stream power, and effective stream power by using the entire dataset of the four different grain sizes (Fig. 5). The best agreement with transport capacity was obtained using unit stream power (Fig. 5c). However, when a multiple linear regression analysis was used to estimate transport capacity as a function of unit stream power and grain size, it was not significantly affected by grain size ($p = 0.197$). The non-significant effect of grain size on the relationship between transport capacity and unit stream power was somewhat surprising, because grain size has been seen to have considerable effect on mean flow velocity (Ali

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et al., 2011). These results do agree with the findings of previous researchers (Govers and Rauws, 1986; Moore and Burch, 1986; Govers, 1990) in such a way that the unit stream power theory showed greatest potential for estimating transport capacity of overland flow under erodible beds. But they contradict earlier findings in the sense that the exponent of unit stream power was independent of grain size.

The regression analysis between transport capacity and unit stream power produced the following relationship:

$$T_c = 2326.6\omega_u^{2.89} \quad R^2 = 0.87 \tag{6}$$

Where T_c (kg m^{-1} s^{-1}) is the sediment transport capacity and ω_u (m s^{-1}) is the unit stream power.

The performance of shear stress was poor as compared to other composite predictors (Fig. 5a). The possible reason for its poor performance is that the shear stress required to attain a certain value of transport capacity for fine grains (i.e. 0.230 mm) is significantly lower than that needed to attain the same transport capacity for coarse grains i.e. 1.022 mm (Fig. 5a). Moreover in a multiple linear regression analysis of shear stress and grain size to estimate transport capacity, the effect of grain size was significant ($p << 0.05$). Shear stress is generally not a good predictor for overland flow under erodible beds (Govers and Rauws, 1986; Govers, 1992), because part of shear stress is dissipated on bed irregularities for sediment detachment (i.e. form shear stress) but does not contribute to sediment transport.

Stream power and effective stream power produced, when plotted against transport capacity, relatively lower scatter as compared to shear stress, thus both resulted in reasonable relationships with transport capacity (Fig. 5b and d). Similar to the shear stress results, grain size had a significant impact ($p < 0.05$) on transport capacity in the multiple linear regression analysis, relating transport capacity to stream power or effective stream power and grain size using all data. Dependency of transport capacity on grain size in this case is due to the fact that both predictors are a function of shear stress. Several other researchers also found that the relationship between transport capacity

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and effective stream power is dependent on grain size (Govers, 1990; Everaert, 1991; Ferro, 1998).

In a previous study, it was found that the mean flow velocity on the erodible bed in the same flume could be well predicted from total discharge and median grain size (Eq. 1). Equation (1) can be written as:

$$U = 4.42\frac{Q^{0.506}}{D_{50}^{0.172}} \tag{7}$$

Where U ($\mathrm{m\,s^{-1}}$) is the mean flow velocity, Q ($\mathrm{m^3\,s^{-1}}$) is the total discharge, and D_{50} (m) is the median grain diameter. As it is hard to measure mean flow velocity in the field, the application of Eq. (6) really becomes difficult because unit stream power depends on mean flow velocity (Eq. 4). Incorporating Eq. (7) into Eq. (6) leads to the following description of transport capacity:

$$T_c = 0.17\times10^6\frac{Q^{1.46}}{D_{50}^{0.50}}S^{2.89} \tag{8}$$

Where S ($\mathrm{m\,m^{-1}}$) is the slope gradient. Figure 6 shows the agreement between measured and predicted transport capacity using Eq. (8) and it is clear that the accuracy is rather good under the tested experimental set-up. This suggests that transport capacity can be directly estimated from total discharge, median grain size, and slope gradient, which are relatively easily measured under field condition. Correspondingly, these findings show that the measurements of flow velocity and flow depth are not needed to estimate sediment transport capacity.

4 Conclusions

The results of this study clearly show that slope gradient has a stronger impact on sediment transport capacity than unit discharge and mean flow velocity. This is most

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likely due to the fact that the tangential component of the gravity force increases with slope gradient. In-addition, because bed geometry varies greatly with slope gradient (Gimenez and Govers, 2001, 2002) the relationships of unit discharge and mean flow velocity with transport capacity varied substantially with slope gradient. This indicates that bed form evolution is a feedback mechanism between sediment transport capacity and hydraulic parameters. The results obtained under this study for erodible beds are somewhat different from what the literature shows for non-erodible beds. This is because in case of non-erodible beds, (i) the available flow energy is utilized entirely for sediment transport, instead of dissipating due to bed irregularities, bed form evolution and sediment detachment, and (ii) flow velocity increases steadily with slope gradient.

The experimental results showed that sediment transport capacity is well related to the selected composite force predictors, except shear stress. Unit stream power was the best performing composite predictor for estimation of transport capacity for shallow flows. A weaker relation was obtained between transport capacity and shear stress ($R^2 = 0.61$), since part of shear stress is used to detach sediment particles from soil mass i.e. form shear stress. Despite the fact that stream power and effective stream power are functions of shear stress, both exhibited good potential for prediction of transport capacity, although the exponents of their relationships were found to be dependent on grain size. Among the selected composite predictors, unit stream power is preferred over other composite predictors, because (i) grain size has a non-significant effect on the relation between transport capacity and unit stream power, and (ii) mean flow velocity can be easily predicted from total discharge and median grain size (Ali et al., 2011).

Overall, these results are entirely different from the results obtained from experiments with non-erodible beds, because both grain shear stress and form shear stress are utilized for sediment transport in the case of non-erodible beds (Zhang et al., 2009). The derived unit stream power based equation (Eq. 8) shows promise for use in physically based soil erosion models to more precisely estimate sediment transport capacity. More precise estimation of transport capacity is important in the ongoing challenge to better predict and manage soil erosion. Nonetheless, the equation suggested from this study was derived for non-cohesive narrowly graded sands, thus its validity needs to be further evaluated for cohesive soils.

Acknowledgements. The experiments were carried out in hydraulic laboratory, Wageningen University with the technical assistance and cooperation of Land Degradation and Development Group, whose support is gratefully acknowledged. Financial support of the work presented in this research paper from the Higher Education Commission, Pakistan (Grant No. 120076) is also gratefully acknowledged.

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Table 1. Experimental data.

Run No.	D_{50} (mm)	Slope (%)	Unit discharge ($10^{-3}\,m^2\,s^{-1}$)	Measured flow depth (m)	Measured sediment transport capacity ($kg\,m^{-1}\,s^{-1}$)
1	0.230	5.2	0.17	0.00120	0.0008
2				0.00120	0.0009
3			0.33	0.00140	0.0068
4				0.00140	0.0062
5			0.67	0.00200	0.0229
6				0.00200	0.0312
7		8.7	0.17	0.00115	0.0099
8				0.00115	0.0076
9			0.33	0.00155	0.0314
10				0.00155	0.0373
11			0.50	0.00160	0.0450
12				0.00160	0.0601
13		13.2	0.17	0.00115	0.0195
14			0.33	0.00140	0.0677
15			0.50	0.00205	0.1337
16		17.6	0.07	0.00085	0.0145
17				0.00085	0.0175
18			0.17	0.00100	0.0544
19				0.00100	0.0505
20	0.536	5.2	0.17	0.00093	0.0014
21				0.00093	0.0014
22			0.33	0.00160	0.0063
23				0.00160	0.0067
24			0.67	0.00260	0.0162
25				0.00260	0.0204
26		8.7	0.17	0.000895	0.0074
27				0.000895	0.0065
28			0.33	0.00150	0.0228
29				0.00150	0.0238
30			0.50	0.00220	0.0336
31				0.00220	0.0361
32		13.2	0.17	0.00100	0.0229
33				0.00100	0.0189
34			0.33	0.00150	0.0587
35				0.00150	0.0519
36			0.50	0.00180	0.0952
37				0.00180	0.0890
38		17.6	0.07	0.00097	0.0086
39				0.00097	0.0095
40			0.17	0.00100	0.0347
41				0.00100	0.0438

Table 1. Continued.

Run No.	D_{50} (mm)	Slope (%)	Unit discharge ($10^{-3}\,m^2\,s^{-1}$)	Measured flow depth (m)	Measured sediment transport capacity ($kg\,m^{-1}\,s^{-1}$)
42	0.719	5.2	0.33	0.00185	0.0064
43				0.00185	0.0071
44			1.00	0.00330	0.0354
45				0.00330	0.0278
46			2.07	0.00515	0.0838
47				0.00515	0.0657
48		8.7	0.17	0.00115	0.0084
49				0.00115	0.0066
50			0.33	0.00125	0.0236
51				0.00125	0.0249
52			1.00	0.00295	0.0870
53				0.00295	0.0888
54		13.2	0.17	0.00115	0.0192
55			0.33	0.00170	0.0491
56			0.50	0.00180	0.0911
57		17.6	0.07	0.00075	0.0073
58				0.00075	0.0072
59			0.17	0.00135	0.0365
60				0.00135	0.0308
61	1.022	5.2	0.33	0.00195	0.0045
62				0.00195	0.0044
63			1.00	0.00390	0.0252
64				0.00390	0.0260
65			2.07	0.00565	0.0670
66				0.00565	0.0651
67		8.7	0.17	0.00125	0.0042
68				0.00125	0.0043
69			0.33	0.00195	0.0173
70				0.00195	0.0179
71			1.00	0.00305	0.1063
72				0.00305	0.0784
73		13.2	0.17	0.00120	0.0118
74			0.33	0.00175	0.0437
75			0.50	0.00250	0.0794
76		17.6	0.07	0.00120	0.0018
77				0.00120	0.0020
78			0.17	0.00150	0.0170
79				0.00150	0.0187
80			0.33	0.00195	0.0946
81				0.00195	0.0976

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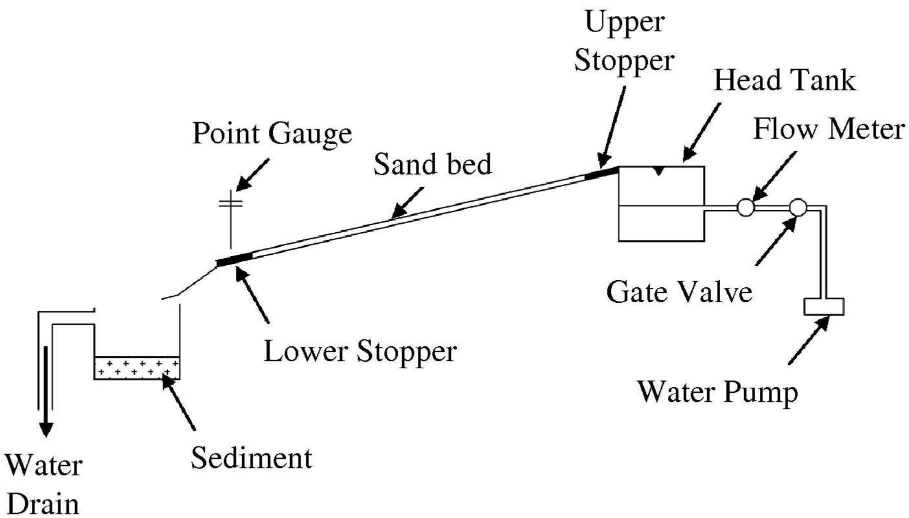

Fig. 1. Experimental flume utilized for sediment transport capacity measurements in relation to hydraulic and sediment parameters.

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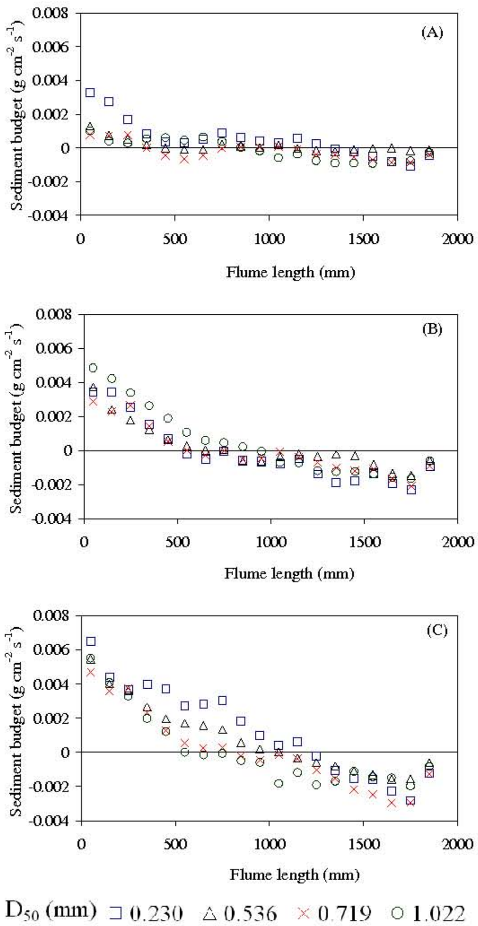

Fig. 2. Sediment budget along the flume length corresponding to unit discharges of **(A)** 0.17 **(B)** 0.33 **(C)** 0.50 × 10^{-3} m^2 s^{-1} at a slope of 13.2 % for different grain size classes.

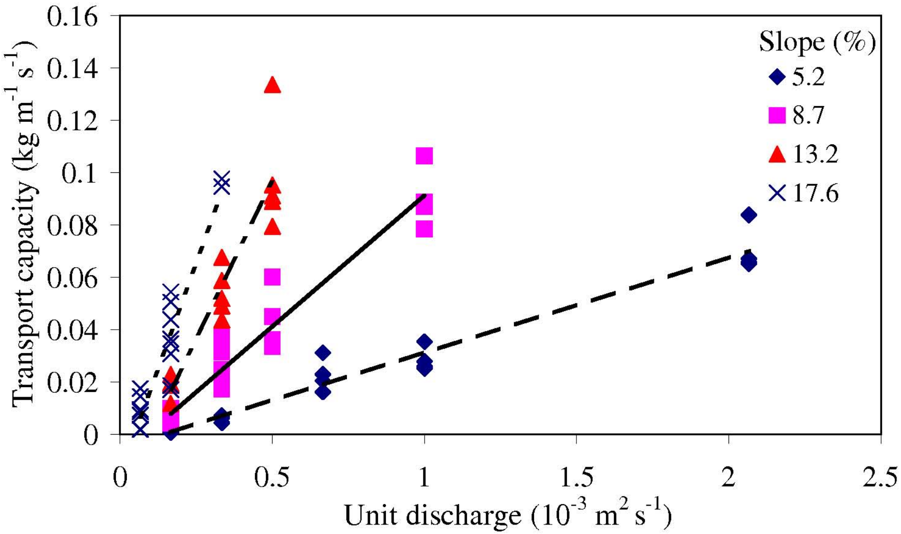

Fig. 3. Relationship between measured sediment transport capacity and unit discharge for different slope classes. All sediment types were included.

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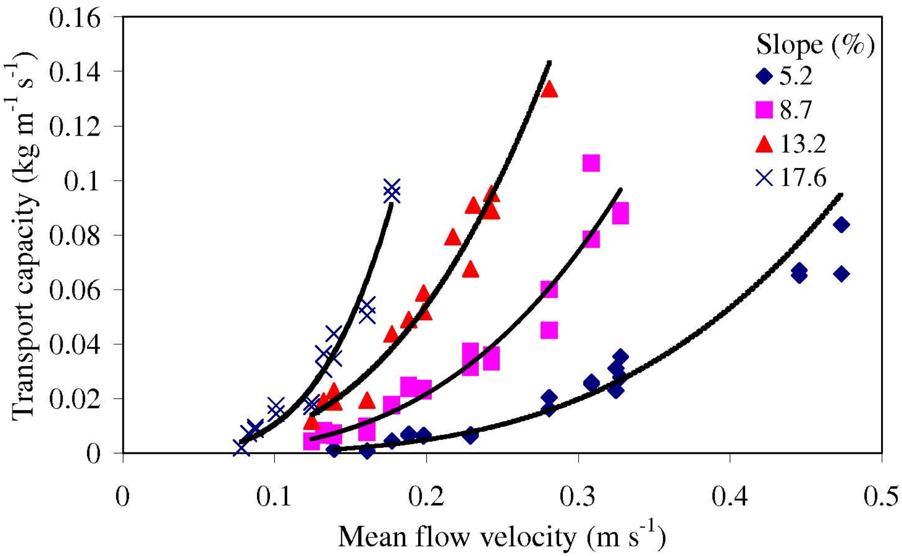

Fig. 4. Relationship between measured sediment transport capacity and mean flow velocity for different slope classes. All sediment types were included.

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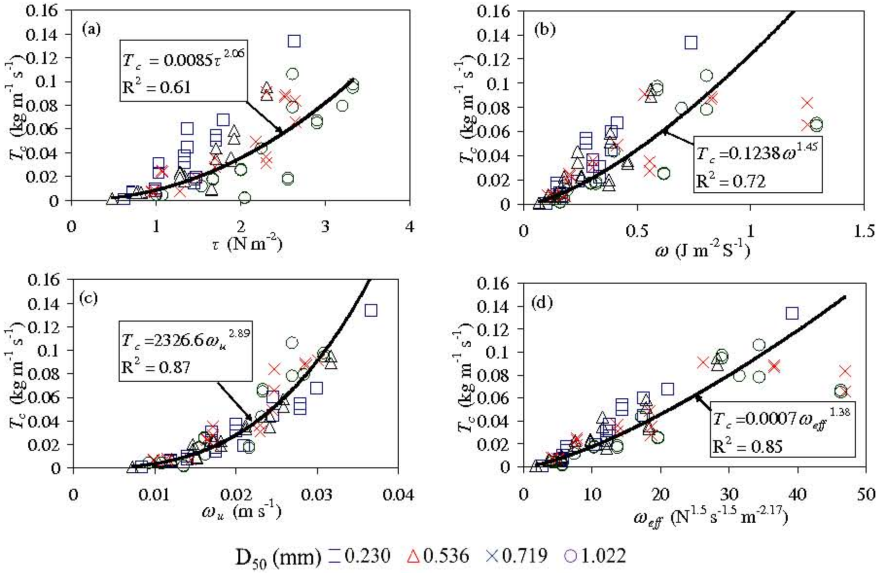

Fig. 5. Sediment transport capacity (T_c) as a function of **(a)** shear stress, τ **(b)** stream power, ω **(c)** unit stream power, ω_u **(d)** effective stream power, ω_{eff} for four grain sizes.

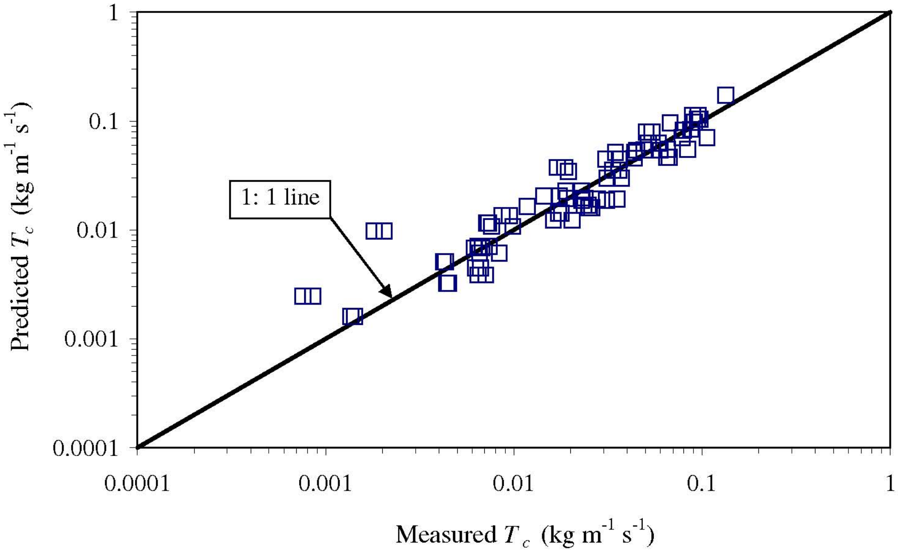

Fig. 6. Comparison between measured and predicted sediment transport capacities by using Eq. (8).