Experiments on sediment deposition by overland flow

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Abstract Experiments were conducted to evaluate the influence of sediment concentration, slope and discharge on sediment deposition rates and patterns associated with a reduction in bed slope. Analysis of the data shows that up to a certain unit discharge a simple settling equation without a transport term gives a good prediction of the sediment delivery ratio and the grain-size distribution of the deposited and the exported material. Only when this critical unit discharge is exceeded do properties of the overland flow influence the sediment delivery outcomes. The presently available data do not allow the best model for predicting deposition rates in this domain to be identified, but clearly indicate the necessity of a threshold value in any transport or re-entrainment function which is used to model deposition.

INTRODUCTION

The quantitative description of sediment transport across areas of deposition is an essential part of assessing the off-site effects of soil erosion on hillslopes. An understanding of sediment delivery from the hillslopes to the stream requires information on both soil erosion and sediment deposition. Although a vast number of studies of different aspects of soil erosion processes at various spatial and temporal scales exist, there are very few detailed studies on sediment transport through net deposition zones.

Consequently, most of the equations describing depositional phases in physically based erosion–deposition models remain largely untested, although predictions of sediment delivery and sediment enrichment are very sensitive to the performance of the deposition equations.

EXPERIMENTAL SET-UP

In the experiments deposition occurring in a flume 2.6 m long, 0.117 m wide, with a 2% slope was studied (Fig. 1). Homogeneous mixtures of water and silty soil were introduced at the top of a lead-in flume through a calibrated discharge measurer. This lead-in flume had a bed slope of 10% and a length of 1 m. At its lower edge it connected into the 2% sloping flume where deposition occurred. Flow rates ranged

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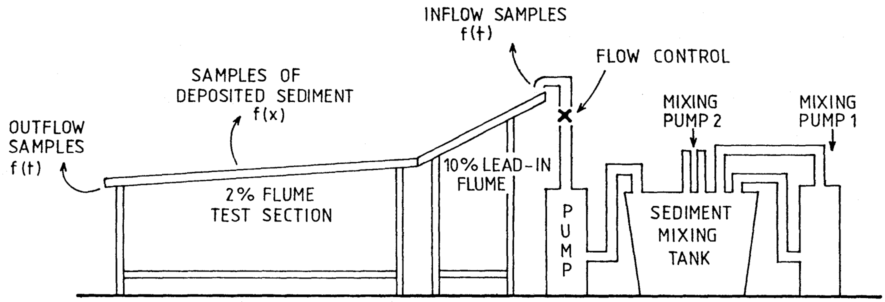

Fig. 1 Schematic illustration of the experimental set-up.

from 0.0003 to 0.0016 m^3 s^{-1} and sediment concentrations ranged from 40 to 180 kg m^{-3}. Each experiment was conducted using a constant discharge and a constant inflow sediment concentration throughout the experimental run. Sediment was prepared using a silty soil (dispersed: 19% clay, 72% silt, 9% sand) that had the stones removed passing a 5 mm screen and was mixed with water in a 100-litre tank for more than 30 min.

During each experiment velocities in the depositional flume section were measured with dye tracing. Samples were collected at the inflow (periodically) and additionally at the end of the flume (each minute), and were subsequently used to assess the sediment concentration and the grain-size distribution. The duration of individual experimental runs ranged from 5 to 24 min depending on the flow discharge used.

The pattern of deposition was obtained by analysis of samples taken every 20 cm down the flume from the point at which the two flumes joined. Grain-size analyses were completed with the Coulter LS-100 and converted to sieve-pipette data (Beuselinck *et al.*, in press). All samples were analysed for their undispersed size distribution. Selected samples were analysed for dispersed size distribution. There was only a slight difference between dispersed and undispersed samples which indicates that most aggregates broke down during pumping, as was concluded in the study of Krishnappan (1993).

RESULTS

Figure 2 shows the sediment delivery ratio (SDR) *vs* unit discharge for all experiments. There is a clear change in relational gradient around a unit discharge of 0.0009 m^2 s^{-1}. At unit discharges below this critical value the SDR increases slowly with unit discharge. In this lower unit discharge range the results suggest that for a given unit discharge the SDR appears to be independent of the inflow sediment concentration. Thus, increasing the inflow sediment concentration increases, by the same ratio, the outflow sediment concentration. At unit discharges higher than this critical value sediment delivery increases rapidly. For a given unit discharge in this range the SDR decreases with increasing inflow sediment concentration.

As expected, the experimental results show that sedimentation is a highly selective process (Fig. 3). Up to a unit discharge of *ca.* 0.0009 m^2 s^{-1}, coarse particles (>32 μm) cannot be maintained in suspension and are deposited quickly. Fine particles (<8 μm) are easily entrained and remain almost entirely in suspension. Figure 3 shows that at low flow rates sediment delivery ratios for the fractions 2–4 μm and 4–8 μm are somewhat higher than for the fraction <2 μm. Also, the SDR is higher for the sand fraction (>63 μm) than for the 32–63 μm fraction.

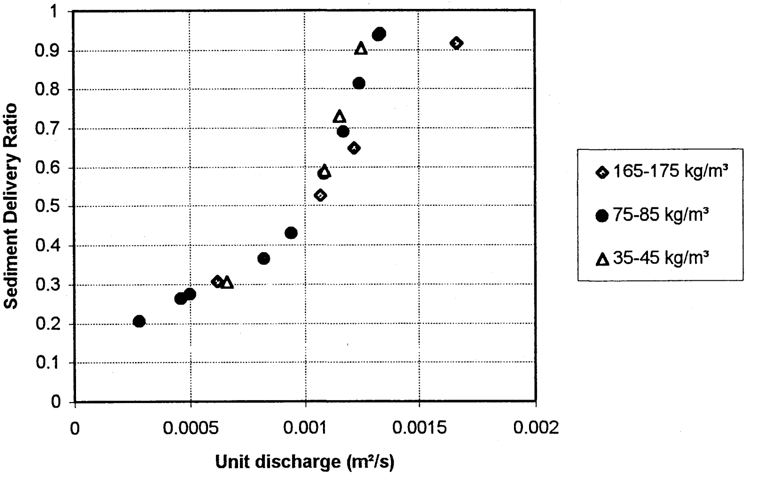

Fig. 2 Total sediment delivery ratio *vs* unit discharge for experiments conducted with a inflow sediment concentration ranging respectively from 35 to 45 kg m^{-3}, from 75 to 85 kg m^{-3} and from 165 to 175 kg m^{-3}.

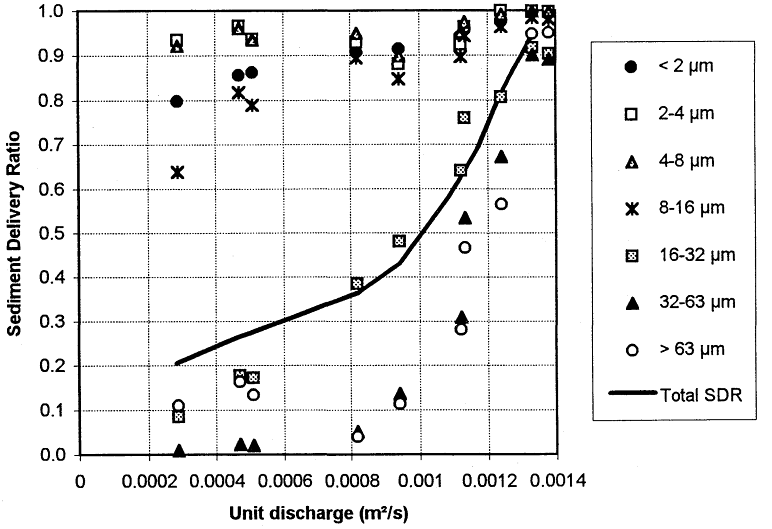

Fig. 3 Sediment delivery ratio *vs* unit discharge for seven grain-size classes for experiments conducted with a inflow sediment concentration ranging from 75 to 85 kg m^{-3}.

DISCUSSION

The simple settling theory

The simplest model available to predict sediment deposition is the simple settling theory (SST) also described by Dabney *et al.* (1995). The multiple class simple settling theory assumes that sediment deposition is a steady settling process in which particles settle without interference and are trapped when they reach the bed surface. For this system the mass conservation equation is given by:

$$\delta C_i/\delta x = -(v_i/q)\, C_i \tag{1}$$

where:
C_i = local sediment concentration of fraction i (kg m^{-3});
q = discharge per unit width (m^3 s^{-1} m^{-1});
x = distance (m);
v_i = settling velocity of fraction i (m s^{-1}).

Integrating, using the boundary condition that the local sediment concentration (C_i) equals the initial sediment concentration ($C_{i\ \mathrm{in}}$) at $x = 0$, yields the fraction of each particle size class that reaches a distance x without settling:

$$C_i/C_{i\ \mathrm{in}} = \exp[-(v_i/q)\, x] \tag{2}$$

The total SDR at the end of the flume is then the sum of the fractions of each grain-size class reaching the outlet. The SST assumes that sediment re-entrainment of previously deposited sediment is negligible. It is noteworthy that equation (2) does not contain a slope term. Furthermore, equation (2) predicts that the SDR is independent of the inflow sediment concentration.

Evaluation of the simple settling theory

Equation (2) was then used to evaluate the experimental results. The sediment delivery ratio was calculated for the seven size classes shown in Fig. 3. Fall velocities for each size fraction were calculated using the equations developed by Dietrich (1982).

Figure 4 shows that the SST predicts very well the observed overall SDR for unit discharges up to *c.* 0.0009 m^2 s^{-1}. For higher unit discharges, the observed SDR exceeds the predicted SDR. The observed independence of the SDR of the inflow sediment concentration for unit discharges <0.0009 m^2 s^{-1} is also in agreement with the predictions of the SST.

If the SDR is calculated separately for each size class, it can be seen that there is a good overall agreement between the observed and predicted SDR for the various classes for unit discharges <0.0009 m^2 s^{-1}, indicating that SST is capable of predicting both total sediment output and size selectivity in this domain (Fig. 5). There are, however, some discrepancies. The simple settling theory overpredicts the clay (<2 μm) and underpredicts the sand (>63 μm) export. This implies that mechanisms other than simple settling may well be operative on the clay and the sand fraction. Dabney *et al.* (1995) also observed consistent overprediction of fine-

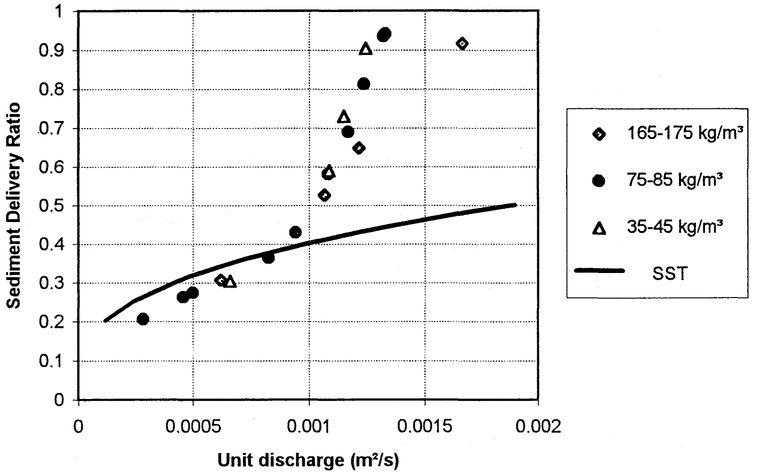

Fig. 4 Predicted (simple settling theory—equation (2)) and measured sediment delivery ratio *vs* unit discharge.

sediment export using only the settling theory. Possible explanations are the flocculation and coagulation of fine sediment, the "sweeping" of fine sediment out of the flow by coarser particles and the effects of Brownian motion, which is especially significant for smaller particles (Dabney *et al.*, 1995; Lick, 1982). The underprediction of the export of coarse sediment (>63μm) may be explained by so-called uncommon selectivity (Savat, 1982; Govers, 1989): as the flow in this domain was laminar, deposited sand particles may be more easily transported by rolling over the bottom of the flume than the finer fractions.

If a threshold unit discharge of *c.* 0.0009 m^2 s^{-1} is exceeded, more sediment is exported than predicted by SST. This implies that a significant amount of sediment is transported by the flow over the depositional area. Several models do exist which

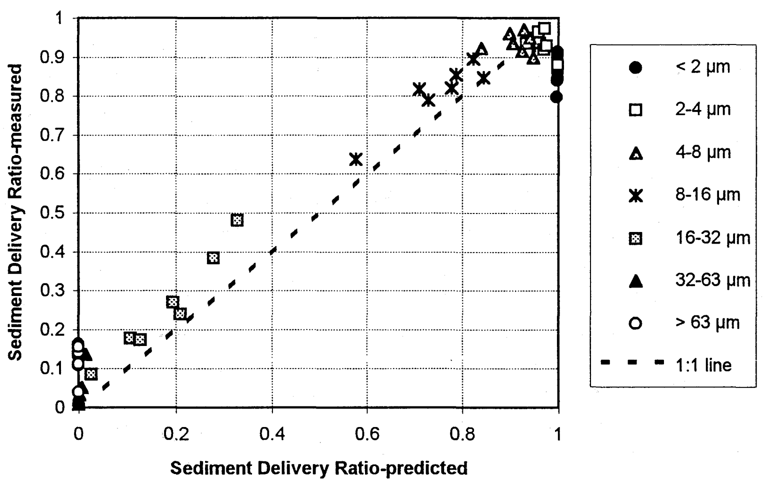

Fig. 5 Predicted (simple settling theory—equation (2)) *vs* measured sediment delivery ratios for seven grain-size classes for experiments conducted with a unit discharge lower than 0.0009 m^2 s^{-1}.

should be capable of predicting sediment deposition under these circumstances. Some of these models are based on the transporting capacity principle (e.g. WEPP—Foster *et al.* (1995), EUROSEM—Morgan *et al.* (in press)). These models predict the local net deposition rate based on the difference between the transporting capacity of the flow and the actual sediment load on the one hand and particle fall velocity on the other hand. Hairsine & Rose (1992a,b) follow a different approach: in their model the local net deposition rate is calculated as the difference between gross deposition and re-entrainment.

The presently available data do not allow us to conclusively evaluate which modelling approach best simulates our data. However, the presence of a significant amount of coarse material (>32 μm) in the outflow at higher unit discharges indicates re-entrainment of the previously deposited sediment.

On the other hand, the experiments clearly indicate that for low-energy flow, deposition can adequately be modelled using simple settling theory, while this is no longer true once a critical unit discharge is exceeded. This illustrates the necessity of a (set of) threshold value(s) for sediment transport or re-entrainment in any model that is used to predict deposition in this domain.

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