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The influence of rainfall on sediment transport by overland flow over areas of net deposition

L. Beuselinck[a], G. Govers[a,b,*], P.B. Hairsine[c], G.C. Sander[d], M. Breynaert[a]

[a]Laboratory for Experimental Geomorphology, Katholieke Universiteit Leuven, Redingenstraat 16, 3000 Leuven, Belgium
[b]Fund for Scientific Research, Flanders, Belgium
[c]CSIRO Land and Water and the Co-operative Research Centre for Catchment Hydrology, P.O. Box 1666, Canberra 2601, Australia
[d]Department of Civil and Building Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK

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Abstract

Overland flow is often only a few millimetres deep. Consequently, the potential for raindrop impact to affect flow hydraulics and sediment transport is high. Furthermore, the relative importance of rainfall impact is highest for shallow low-energy flows on low slopes. In such flows net sediment deposition may occur. Therefore, laboratory experiments were conducted to study sediment deposition in the presence of rainfall over a range of hydraulic conditions. In order to investigate the impact of raindrops on sediment deposition by overland flow, these experimental data were compared to the experimental data collected in the absence of raindrop impact. Comparison of the experimental data shows that raindrop impact retards the flow velocity and has a clear positive effect on sediment delivery. Under rainfall significantly more coarse sediment is transported over areas of net sediment deposition. Subsequently, the experimental results are used to evaluate a multi-class net deposition theory, describing sediment transport and sediment sorting over areas of net deposition in the presence of both raindrop impact and flow-driven processes. The multi-class theory is calibrated using part of the experimental data. Evaluation of the model predictions using the other part of the data shows that the optimised model is able to accurately predict sediment delivery and sediment sorting over areas of net deposition.

Keywords: Overland flow; Sediment deposition; Sediment sorting; Raindrop impact

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1. Introduction

Three different types of sediment transport by water erosion can be differentiated (Moss et al., 1979). Sediment can be transported by overland flow, by rainsplash and by the combination of overland flow and rainfall impact. Beuselinck et al. (1999a) presented experimental results on sediment transport by overland flow over an area of net deposition in the absence of raindrop impact. These experimental data were used to evaluate the simple settling theory, in which sediment deposition is described as only settling based on the settling velocity distribution of the inflow sediment (Beuselinck et al., 1999b), and the Hairsine et al. (2001) sediment deposition algorithm (Beuselinck et al., 2001a,b).

Sediment transport by raindrop impact in the absence of an overland flow layer has also been extensively studied (e.g. Moeyersons and De Ploey, 1976; Savat, 1981; Poesen and Savat, 1981; Moss and Green, 1983). If a raindrop falls on a horizontal soil

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* Corresponding author. Tel.: +32-16-32-6437; fax: +32-16-32-6400.
E-mail address: gerard.govers@geo.kuleuven.ac.be (G. Govers).

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surface, net raindrop splash transport rate should be nil (Moss et al., 1979). The effect of slope and wind results in a net transport direction for the detached sediment (Moss et al., 1979; Poesen, 1985).

Palmer (1964) first studied the impact of a thin water layer on soil loss due to raindrop impact. Palmer stated that the rainfall impact increases until a critical depth is reached. Once this critical depth is exceeded the raindrop impact decreases. Experimental studies showed that the maximum raindrop impact occurs for water depths of less than one raindrop diameter (Palmer, 1965; Mutchler and Young, 1975; Ghadiri and Payne, 1981). Proffitt et al. (1991) showed experimentally that transport rate decreases linearly with flow depth when flows are deeper than 2–3 mm and shallower than about three drop diameters. For flow depths greater than three drop diameters, Proffitt et al. (1991) showed that the raindrop impact becomes negligible. The decrease in sediment detachment with increasing flow depth can be attributed to an increase in protection of the soil surface by the water layer (Ferreira and Singer, 1985). The efficiency of the raindrop detachment also depends on rainfall intensity and drop diameter (Palmer, 1965; Moss and Green, 1983). Smaller drops are less efficient in detaching sediment. Physical explanation of the efficiency of raindrop impact in the presence of a water layer and visualisation of the water structures formed is given by Tuong and Painter (1974) and Moss and Green (1983).

The effect of raindrop splash on air-born sediment transport is negligible compared to the effect of rainfall on sediment detachment and transport by the flow (Walker et al., 1978; Moss et al., 1979). Raindrops, impacting shallow flowing water, cause suspension, saltation and bed load movement (Moss et al., 1979). Small particles detached by raindrop impact become suspended in the overland flow. These suspended particles rapidly acquire the horizontal velocity of the flow and are transported downslope (Kinnell, 1991). Transport distance depends on the settling velocity of the suspended particles. Larger particles detached by raindrop impact are transported by saltating or by rolling over the bed (Walker et al., 1978). Moss et al. (1979) defined this rain-stimulated transport of sediment 'rain-flow transportation'. Rain-flow transportation is relatively important on low slopes and at low flow conditions, where sediment entrainment by overland flow is negligible. Rain-flow transportation is overshadowed by overland flow entrainment at steeper slopes (Moss et al., 1979; Proffitt and Rose, 1991; Everaert, 1991; Abrahams et al., 1998). Moss (1988), for example, states that sediment entrainment by overland flow becomes dominant on slopes greater than 9%. The relative importance of rain-flow transportation also depends on the erodibility of the soil, on the energy of the stream (Quansah, 1985; Hairsine and Rose, 1991) and on the rainfall intensity (e.g. Kinnell, 1991). Under the same rainfall conditions, the detachability of previously deposited sediment is much higher than the detachability of source material (Hairsine and Rose, 1991; Proffitt et al., 1991).

Most of the above studies were carried out for hydraulic conditions at which net soil erosion occurs. Nevertheless, the relative importance of raindrop impact is highest at low slopes and at low energy of the flow (Moss et al., 1979; Proffitt and Rose, 1991; Everaert, 1991). For these conditions, sediment deposition may occur. Therefore, the objective of this paper is to assess how rainfall impact affects overland flow hydraulics and sediment deposition of silty material at low flow energy. In order to test the impact of rainfall on sediment transport by overland flow, laboratory experiments were conducted to study the combined action of overland flow and rainfall impact on sediment transport over areas of net deposition. The contribution by raindrop impact is assessed by comparing these experimental results with the results obtained in similar experiments conducted in the absence of rainfall (Beuselinck et al., 1999a). Subsequently, the experimental results are used to evaluate the multi-class solution to the Hairsine et al. (2001) net deposition theory (Sander et al., 2001), describing sediment transport and sediment sorting over areas of net deposition in the presence of both raindrop impact and flow-driven processes.

2. Experimental set-up

In order to assess the rainfall impact on sediment transport by overland flow, laboratory experiments were conducted. The same experimental set-up was used as the one described by Beuselinck et al. (1999a). Sediment-laden overland flow was simulated by

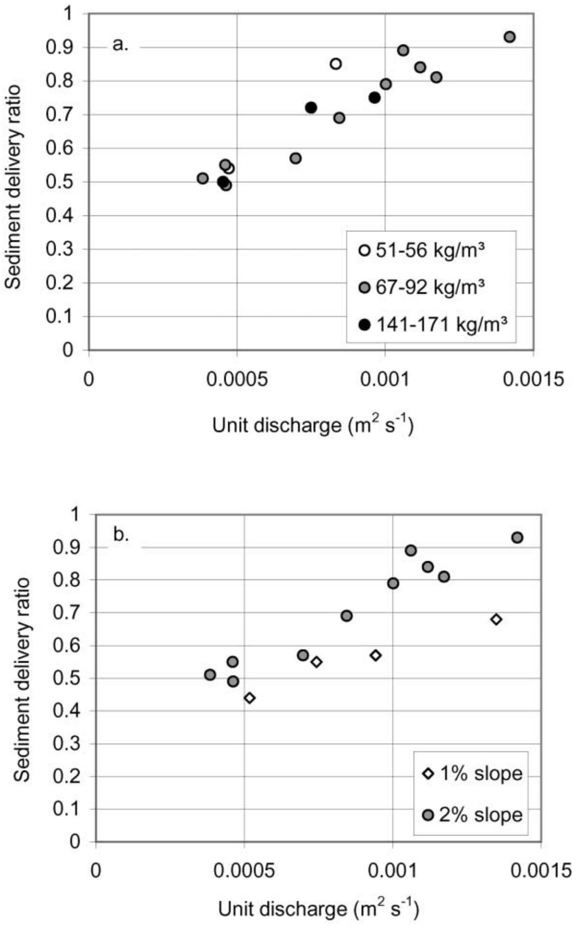

Fig. 1. SDR versus unit discharge (a) for experiments conducted on a 2% slope with three different inflow sediment classes and (b) for experiments conducted with a medium inflow sediment concentration (67–92 kg m^{-3}) on a 1 and 2% slope.

introducing a water and sediment mixture at the top of a lead-in flume. This lead-in flume was connected to the depositional flume at its lower edge. Simulated rainfall impacted the sediment-laden water flowing across the depositional flume.

Rainfall was provided by a single nozzle continuous-spray system (LECHLER, type 460.788). Water was pumped from a water tank at a nozzle pressure of 20.6 kPa, yielding an average rainfall intensity over the plot area of 45 mm h^{-1}. The simulated drop-size distribution is comparable to that of natural rain with a similar intensity (Poesen et al., 1990). Median drop-size diameter is ca. 1.47 mm (Salles et al., 1999).

In total, 19 experiments were carried out. During each experiment all input parameters were kept constant. Unit flow discharge (flow discharge per unit width of the flow) ranged from 0.0003 to 0.0014 m^3 s^{-1} per metre width and inflow sediment concentrations ranged from 50 to 170 kg m^{-3}. As in the experiments conducted in the absence of rainfall, the inflow sediment was almost completely dispersed since most aggregates broke down during pumping in the mixing tank. All experiments were undertaken with silty material (type B, Beuselinck et al., 1999a). For the depositional flume, slopes of 1 and 2% were used.

The same experimental procedure was used as in the experiments conducted in the absence of rainfall impact (Beuselinck et al., 1999a). The effect of raindrop impact on the flow velocity was evaluated by comparing surface flow velocities measured by dye tracing in the presence and absence of rainfall. Grain-size distributions of the inflow, the outflow and the deposited sediment were conducted using laser diffraction (Coulter LS-100, Beuselinck et al., 1998). All sediment samples were analysed for their undispersed size distribution.

3. Results

3.1. Overall sediment delivery ratio

Fig. 1a shows the sediment delivery ratio (= amount of sediment exported out of the flume divided by the amount of inflowing sediment; SDR) versus unit discharge for all rain-impacted flows on a 2% slope. The SDR increases approximately linearly with increasing unit discharge. There is no obvious effect of inflow sediment concentration on overall SDR. Also for the experiments conducted at a 1% slope the SDR increases almost linearly with increasing unit discharge (Fig. 1b). However, the SDR increases less rapidly with increasing unit discharge at a 1% slope than at a 2% slope. Compared to the experiments conducted in the absence of raindrop impact, there is more scatter in the SDR–discharge plot (Beuselinck et al., 1999a). This might be due to more experimental variation in the rain-impacted flows (e.g. spatial distribution of the rainfall, rainfall intensity). Guy et al. (1990) also concluded that,

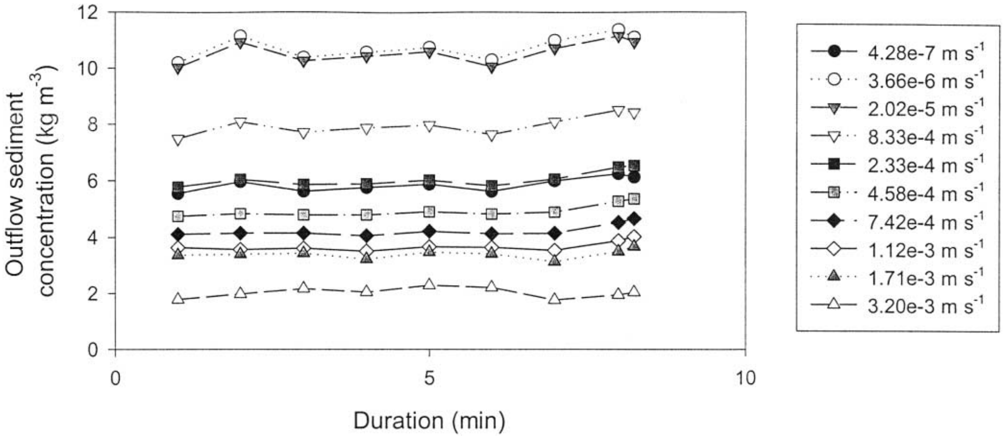

Fig. 2. Outflow sediment concentration of each settling velocity class versus time for an experiment conducted on a 2% slope with a unit discharge of 0.00080 $m^2\ s^{-1}$ and an inflow sediment concentration of 76 kg m^{-3}. Settling velocity classes are obtained by dividing the inflow sediment in 10 classes of equal mass.

although the variability of rainfall intensity was small, the variety of results they obtained can be explained by significant spatial variations in intensity and drop diameter.

Although the slope changes locally during an experiment due to sediment accumulation, there is almost no variation in either the outflow sediment concentration or the grain-size distribution of the exported sediment during the experiments (Fig. 2).

3.2. Grain-size distribution

Sediment transport over an area of net deposition is also in the presence of rainfall a very size selective process. Fine particles (<16 μm) are easily exported out of the flume (Fig. 3a and b), whereas coarser particles are not maintained in suspension. At small unit discharges, about 80% of the coarsest sediment fractions (>32 μm) is deposited within the flume reach. Once the critical unit discharge at a 2% slope, as defined by Beuselinck et al. (1999a) (i.e. 0.00096 $m^2 s^{-1}$), is exceeded, there is a rise in SDR of the coarsest fractions (>32 μm; Fig. 3b). This rise is less pronounced than the sharp rise observed in the experimental data on sediment deposition by unimpacted overland flow (Beuselinck et al., 1999a). For the 1% slope a gradual increase in SDR with increasing discharge is observed for each size fraction (Fig. 3a).

4. Raindrop impact

In order to test the impact of raindrop on flow hydraulics and sediment transport, the experimental data for the impacted flows are compared with the data collected by Beuselinck et al. (1999a) on unimpacted flows.

4.1. Raindrop impact on flow hydraulics

At a 2% slope the regression line fitted to the velocity data for unimpacted flows is statistically different from the slope of the regression line fitted to the velocity data ($\alpha = 0.05$; Fig. 4b) for the unimpacted flows. Statistical analysis shows that there is no significant difference between the slope coefficients of the two regression lines. In contrast, the intercept of the regression line fitted to the velocity data for the unimpacted flows is significantly higher than that for the impacted flows. This implies that, as stated by Savat (1977), the relative importance of raindrop impact on surface flow velocity decreases with increasing discharge. In contrast, at a 1% slope there is no significant difference between the two regression lines obtained in the presence and absence of rainfall ($\alpha = 0.05$) (Fig. 4a).

Thus, in our experiments surface flow velocity retardation due to raindrop impact is rather limited. Since flow velocity reduction due to raindrop impact is highest at the surface (Glass and Smerdon, 1967), it

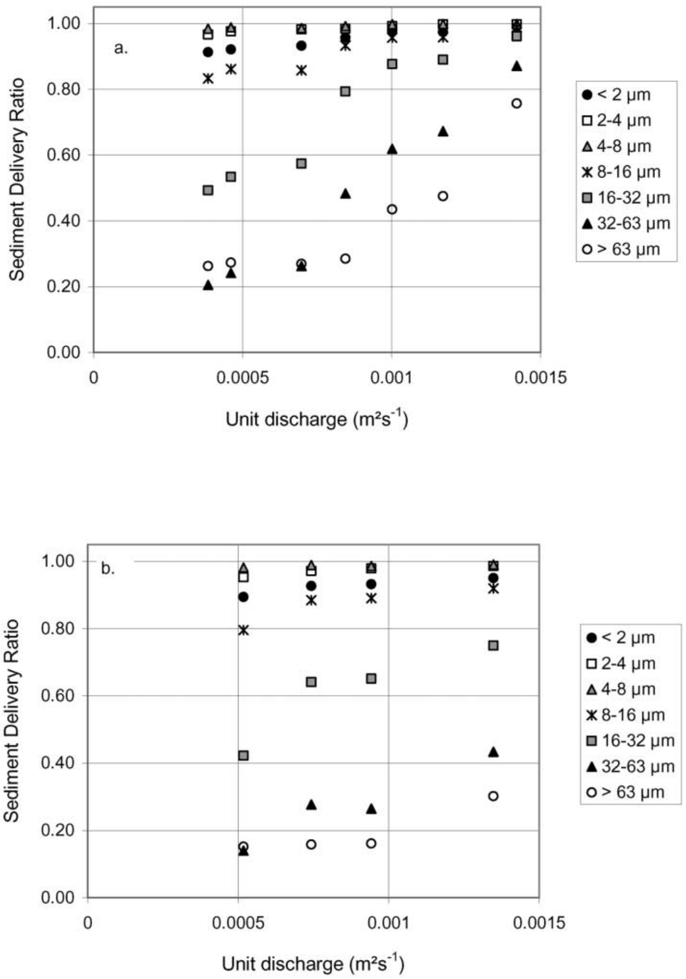

Fig. 3. SDR versus unit discharge for seven grain-size classes for experiments conducted on (a) a 1% slope and (b) a 2% slope with a medium inflow sediment concentration (67–92 kg m^{-3}).

can be concluded that for our experiments only a limited reduction in mean flow velocity due to raindrop impact took place. Savat (1977) also found that the effect of rainfall on flow velocity is less important than measured by other authors. There are two possible explanations. Firstly, our experiments were conducted at a relative low rainfall intensity (45 mm h^{-1}) and with relative small raindrop sizes (median = 1.47 μm) compared to other experimental studies (e.g. Smerdon, 1964; Kinnell, 1991), and Yoon and Wenzel (1971) showed that the reduction in flow velocity is positively related to rainfall intensity. Secondly, in this study, surface flow velocities were measured by dye tracing, whereas most studies investigating rainfall impact on shallow flows use pressure transducers (e.g. Shen and Li, 1973; Kinnell, 1991). In the present case, it was impossible to use pressure transducers due to the accumulation of sediment on the flume bed. However, it is doubtful whether dye tracing is accurate enough to measure small changes in flow velocity due to raindrop impact. Guy et al. (1990) also used dye tracing to determine surface flow velocity in sediment-laden sheet flow. They measured surface flow velocities for raindrop impacted flow and found that these velocities were not significantly different from those predicted by a

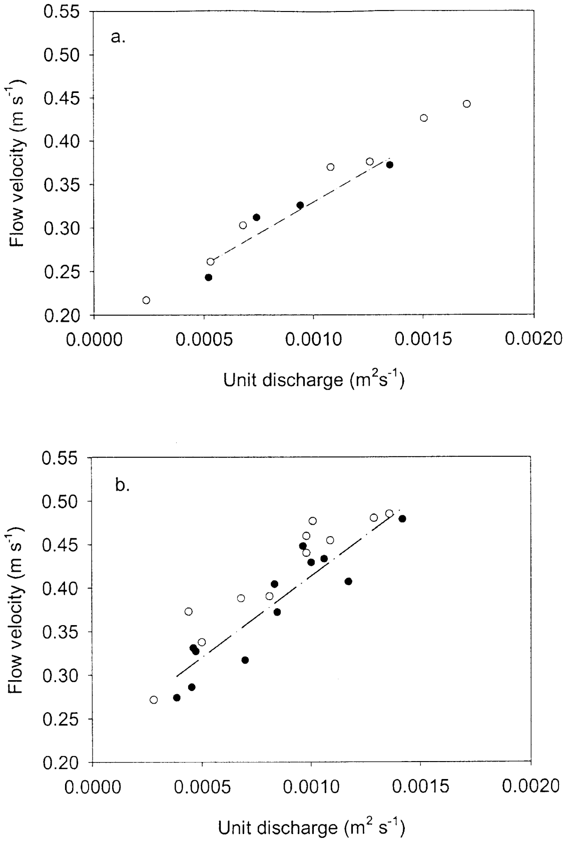

Fig. 4. Surface flow velocities and regression relationships for experiments conducted on (a) a 1% slope and (b) a 2% slope with a medium sediment concentration (67–92 kg m^{-3}) in the presence and absence of rainfall (6: no raindrop impacted flow; 1: raindrop impacted flow).

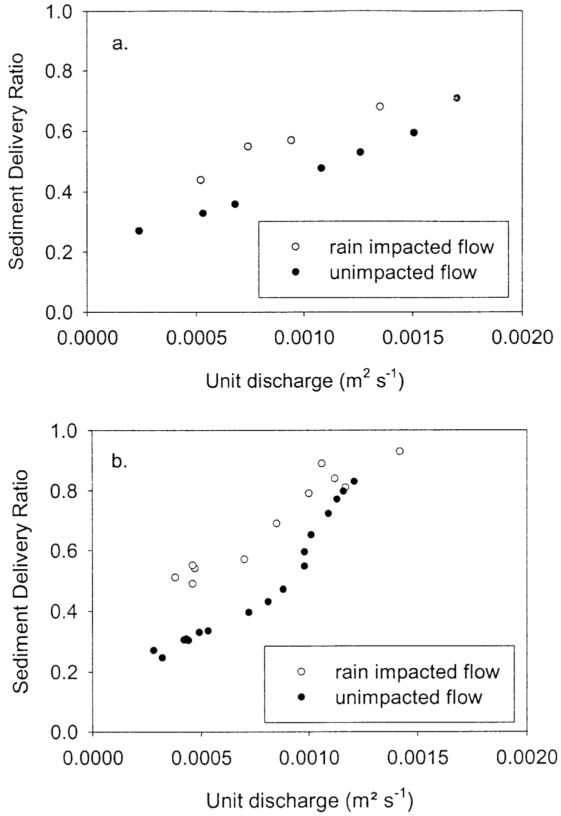

Fig. 6. SDR versus unit discharge for both rainfall impacted and unimpacted experiments conducted on (a) a 1% slope and (b) a 2% slope with medium inflow sediment concentrations (67–92 kg m^{-3}).

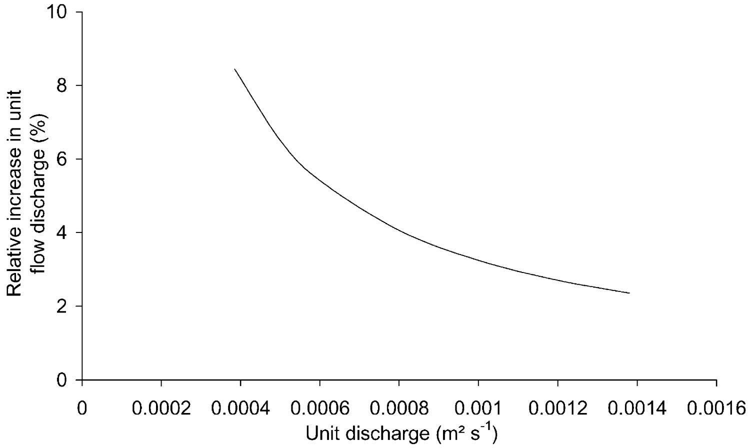

Fig. 5. Relative increase in unit discharge at the flume outlet due to rainfall impact (rainfall intensity of 45 mm h^{-1}).

smooth surface, unimpacted, clear-water model. They attributed this finding to flow retardation by the rainfall being compensated for by a reduction in flow resistance due to high-sediment concentrations and by the role of the flume surface, which may absorb the raindrop energy in very shallow flows.

Fig. 5 shows the relative increase in flow discharge (flow discharge at the end of the flume divided by discharge at the beginning of the flume) at the end of the flume for the rainfall intensity used in our experiments. If rainfall is uniformly distributed over the flume, flow discharge increases linearly with distance on the flume. Evidently, the increase is thus maximal at the flume outlet. Fig. 5 shows that especially at higher flow conditions, the relative increase in flow discharge due to rainfall is rather limited for the rainfall intensity used.

4.2. Raindrop impact on sediment transport

Fig. 6a and b compares the SDR's of rain-impacted and unimpacted flows on 1 and 2% slopes. On 2% slopes, the estimated ratio of flow depth to median drop diameter is between 1.3 and 2.5, whereas on 1% slopes, the ratio lies between 1.8 and 3.0. Consequently, flow depths for all discharges studied are smaller than three times the median raindrop diameter. These results show that, under these circumstances, there is a significant increase in sediment delivery due to raindrop impact. On 2% slopes, rainfall has the greatest effect on the SDR at low flow discharges. At higher discharges, the effect of rainfall on the SDR diminishes.

These observations can be explained as follows. Below the threshold value at which there is a sharp rise in the transport capacity of unimpacted flow (Beuselinck et al., 1999a), the influence of flow energy on transport capacity is negligible. In this situation, the flow is unable to re-entrain significant amounts of previously deposited sediment. Thus, the SDR of the unimpacted flow depends only on the fall velocities of the particles and on the velocity of the flow. In the Hairsine–Rose theory (1991), it is assumed that previously deposited sediment particles are lifted into the water layer as a results of raindrop impact. Hairsine and Rose (1991) label this process 'rainfall re-detachment'. Re-detached sediment is mixed within the water layer, and these suspended particles rapidly acquire the horizontal velocity of the flow. These particles return to the accumulating deposited layer, as transport capacity is negligible. However, not all sediment will immediately be redeposited on the flume bed. The rate of sediment deposition depends both on the sediment fall velocity and on the horizontal flow velocity. Part of the previously deposited sediment is thus exported out of the flume by successive trajectories, which is the net result of re-detachment by raindrop impact and deposition by settling. At discharges above the threshold value, previously deposited sediment is re-entrained by the flow (Beuselinck et al., 1999a, 2001a,b). At these discharges, sediment re-detachment and re-entrainment occur simultaneously. Both the sediment that is still into suspension and the deposited sediment brought in suspension by flow re-entrainment and rain re-detachment are continuously settling down at a rate dependent on the sediment fall velocity. Consequently at all discharges where net sediment deposition occurs raindrop impact causes an increase in transported sediment concentration due to the described lag period between sediment re-detachment and subsequent deposition.

On both 1 and 2% slopes, the net effect of raindrop impact on SDR stays relatively constant with increasing discharge at low discharges (Fig. 6a and b). Flow depth increases with increasing discharge. Several studies showed the negative effect of increasing flow depth on raindrop detachment (e.g. Palmer, 1965; Mutchler and Young, 1975; Ghadiri and Payne, 1981; Kinnell, 1991). However, an increase in discharge not only results in an increase in flow depth but also in an increase in flow velocity. The decline in sediment detachment due to the increase in flow depth is thus (partially) offset by the more efficient export of the detached sediment due to the higher flow velocity. Moss (1988) and Kinnell (1991) showed clearly that at a constant flow depth the transport rate of detached sediment increases linearly with increasing flow velocity.

At discharges at which most inflow sediment is exported out of the flume the relative importance of raindrop impact on sediment transport is smaller. This suggests that the negative effect of an increase in flow depth on sediment detachment becomes more important at higher flow conditions than the more efficient delivery of the detached sediment due to the increase in flow velocity.

Comparison of Fig. 6a and b indicates that the net effect of the raindrop impact is more pronounced on a 2% slope than on a 1% slope. An increase in bed slope causes both a decline in flow depth and an increase in flow velocity. The positive effect of a reduction in flow depth on rain detachment is thus amplified by a more efficient transport of the detached sediment at higher flow velocities. Therefore, the net raindrop impact on SDR is more important on higher surface slopes.

5. Model description

5.1. Model

Hairsine and Rose (1991, 1992) developed a new model describing the processes of rainfall detachment, entrainment by the flow, sediment deposition, rainfall re-detachment and sediment re-entrainment by the flow. Hairsine and Rose (1991) provided and Proffitt et al. (1991) tested the equilibrium solution to the mass balance equation describing rainfall detachment and deposition in the absence of flow-driven processes. Recently, Hairsine et al. (1999) and Sander et al. (1996) provided the non-equilibrium solution to this equation, describing the processes of sediment sorting in the early phases of a runoff event when the deposited layer is developing.

Hairsine et al. (2001) presented the mass balance equation describing sediment transport through areas of net deposition in both presence of raindrop impact and flow-driven processes. Sander et al. (2001) provided a multi-class solution to the mass balance for the case of simultaneous deposition and re-entrainment in the absence of raindrop impact. Beuselinck et al. (2001b) evaluated this approach using experimental data collected for a range of hydraulic conditions. These authors concluded that the multi-class sediment deposition equation proposed by Hairsine et al. (2001) accurately predicts sediment sorting during transport by overland flow over an area of net deposition in the absence of raindrop impact. Here, we describe the multi-class solution for the Hairsine et al. (2001) equation in the presence of both raindrop impact and flow-driven processes. We selected the appropriate solution to the Hairsine et al. (2001) equation taking into account the conditions that applied during the experiments described above.

Hairsine and Rose (1992) described soil erosion of a cohesive soil by sheet flow as the outcome of the rate of rainfall detachment (e_i), the rate of rainfall re-detachment ($e_{\mathrm{d}i}$), the rate of entrainment ($r_{\mathrm{e}i}$), and the rate of re-entrainment ($r_{\mathrm{r}i}$), minus the rate of deposition (d_i) in the presence of sheet flow.

More specifically, if movement of sediment and water is considered to occur in a strip of unit width down a plane surface, then mass conservation of the sediment for this system is given by:

$$\frac{\partial(c_i q)}{\partial x} + \frac{\partial(c_i D)}{\partial t} = e_i + r_{\mathrm{e}i} + e_{\mathrm{d}i} + r_{\mathrm{r}i} - d_i, \qquad (1)$$

where q is the water discharge per unit width of the flow, D is the water depth, c_i is the sediment concentration and the subscript i denotes the sediment class.

The following conditions apply for the sediment deposition experiments:

1. The experiments were conducted with steady inflowing discharge and sediment input. Although the mass of the deposit and the spatial pattern of the deposit vary in time, the experimental data show that the outflow sediment concentration of each settling velocity class was time invariant during the experimental run (Fig. 2). Therefore, water flux and sediment concentration are taken as time invariant when solving Eq. (1). This is probably a simplication as sediment concentrations at other points on the flume than the outlet may have varied with time. However, no experimental data are available to assess this variation.
2. The deposit is continuously accumulating so that in the area under consideration, entrainment of new sediment does not occur. For most experiments, the experimental flume was completely shielded by the deposited mass. This is consistent with the development in Hairsine et al. (2001).
3. Due to the rainfall flow discharge increases with distance on the depositional flume. However, as shown in Fig. 5, the increase in flow discharge is rather limited for the rainfall intensity used in our experiments. Therefore, we assume that the downslope increase in discharge due to rainfall is negligible and that, consequently, flow discharge

remains constant downslope. This simplification greatly reduces the complexity of the solution.

For the above conditions the mass conservation (Eq. (1)) reduces to

$$q\frac{\mathrm{d}c_i}{\mathrm{d}x} = r_{\mathrm{r}i} + e_{\mathrm{d}i} - d_i. \tag{2}$$

Both rain detachment and rain re-detachment are assumed to be non-size-selective (Hairsine and Rose, 1991).

$$e_{\mathrm{d}i} = Ha_{\mathrm{d}}P^p\frac{M_{\mathrm{d}i}}{M_{\mathrm{dt}}}, \tag{3}$$

where H is the fractional shielding of the soil by the deposited layer, a_{d} is the re-detachability of the soil, P is the rainfall rate, p is an exponent, $M_{\mathrm{d}i}$ is the mass of sediment of class i in the deposited layer and M_{dt} is the total mass of the deposited layer per unit area. a_{d} is attenuated by increasing flow depth. This effect is described by

$$a_{\mathrm{d}} = a_{\mathrm{d0}} \qquad \text{for } D \leq D_0, \tag{4}$$

$$a_{\mathrm{d}} = a_{\mathrm{d0}}\left(\frac{D_0}{D}\right)^b \qquad \text{for } D > D_0, \tag{5}$$

where a_{d0} is the maximum value of the re-detachability, D is the flow depth, D_0 is the critical flow depth and b is an exponent.

From Hairsine and Rose (1992), the rate of deposition per unit bed area is given by

$$d_i = \alpha_i v_i c_i, \tag{6}$$

where α_i is the vertical mixing coefficient (= ratio of the sediment concentration of class i adjacent to the bed to the mean sediment concentration of class i), v_i is the representative settling velocity for size class i.

The rate of re-entrainment per unit bed area is given by

$$r_{\mathrm{r}i} = \frac{\alpha_i HF}{g}\frac{\sigma}{(\sigma-\rho)}\left(\frac{\Omega-\Omega_0}{D}\right)\frac{M_{\mathrm{d}i}}{M_{\mathrm{dt}}}, \tag{7}$$

where F is the fraction of stream power used for re-entrainment, g is the acceleration due to gravity, σ is the sediment density, ρ is the water density, Ω is the stream power, Ω_0 is the critical stream power.

Substituting Eq. (5) into Eq. (3) and Eqs. (3), (6) and (7) into Eq. (2) gives

$$q\frac{\mathrm{d}c_i}{\mathrm{d}x} = \frac{\alpha HF}{g}\frac{\sigma}{(\sigma-\rho)}\frac{(\Omega-\Omega_0)}{D}\frac{M_{\mathrm{d}i}}{M_{\mathrm{dt}}} + a_{\mathrm{d0}}\left(\frac{D_0}{D}\right)^b P^p\frac{M_{\mathrm{d}i}}{M_{\mathrm{dt}}} - \alpha_i v_i c_i. \tag{8}$$

As mentioned earlier, the depositional mass is continuously accumulating on the experimental flume. Consequently, the flume was totally shielded by the deposited sediment, so that $H = 1$. Furthermore, an additional simplification is made in this derivation by assuming that the α_i-term (i.e. the vertical mixing coefficient) is independent of settling velocity class and that, consequently, α is a fixed constant.

Flow depth is given by the generalised depth-discharge equation

$$D = \left(\frac{q}{K}\right)^{\frac{1}{m}}, \tag{9}$$

where K and m are hydraulic constants.

Substituting Eq. (9) into Eq. (8) results in

$$q\frac{\mathrm{d}c_i}{\mathrm{d}x} = \gamma f_i(x) - \alpha v_i c_i, \tag{10}$$

where

$$\gamma = \frac{\alpha F}{g}\frac{\sigma}{(\sigma-\rho)}K^{\frac{1}{m}}q^{-\frac{1}{m}}(\Omega-\Omega_0) + a_{\mathrm{d0}}\left(D_0K^{\frac{1}{m}}q^{-\frac{1}{m}}\right)^b P^p$$

and $\quad f_i(x) = \dfrac{M_{\mathrm{d}i}}{M_{\mathrm{dt}}}.$

Eq. (10) is identical in form to the resulting multi-class equation in the absence of rainfall impact. Making the simplification that flow discharge is independent of distance downslope allows one to solve the mass continuity equation in the same way in the presence of rainfall as in the absence of rainfall (Sander et al., 2001). Consequently, as in the absence of rainfall, the resulting set of coupled ordinary differential equations can be solved using the exact analytical closed form solution to Eq. (10) presented by Sander et al. (2001).

Table 1
Experimental and input parameters for the Hairsine et al. net deposition algorithm in the presence of rainfall

	Symbol	Description	Value
Experimental variables	q	Unit discharge	0.00034–0.00138 $m^2 s^{-1}$
	c_{in}	Inflow sediment concentration	51–171 kg m^{-3}
	S	Slope	0.01–0.02
Input parameters	ρ	Water density	1000 kg m^{-3}
	σ	Sediment density	2600 kg m^{-3}
	K	Hydraulic parameter	10–14
	m	Exponent	1.66
	α	Vertical mixing coefficient	1
	v_i	Settling velocity range	4.3×10^{-7}–3.2×10^{-3} m s^{-1}
	Ω_0	Threshold of re-entrainment	0.185–0.20 W m^{-2}
	F	Re-entrainment parameter	0.0013
	P	Rainfall intensity	0.0000125 m s^{-1}
	p	Exponent	1
	D_0	Critical flow depth	0.002 m
	b	Exponent	0.66
	a_{d0}	Re-detachability parameter	Optimised parameter (kg m^{-3})

5.2. Input parameters

The input parameters to the net deposition algorithm are listed in Table 1. The K and the m terms are related to the flow hydraulics. Beuselinck et al. (2001a) showed that for experiments conducted at relatively low slopes normal flow depth in unimpacted flows is described well by Manning's equation (Manning's $n = 0.10$). This is not necessarily the case for rain-impacted flows, since rain-impact retards the flow velocity. In the rain-impacted experiments presented in this paper, flow retardation due to raindrop impact is limited (Fig. 4). As a result, the same Manning's n can be used to predict flow velocity (Fig. 7).

Proffitt et al. (1991) assumed that the term α_i (the ratio of the sediment concentration adjacent to the bed to the mean concentration across the entire depth) equals unity in rain-impacted flows, since the raindrop impact and the flow-induced turbulence is likely to mix the sediment uniformly trough the water layer. Beuselinck et al. (1999b) showed that even in

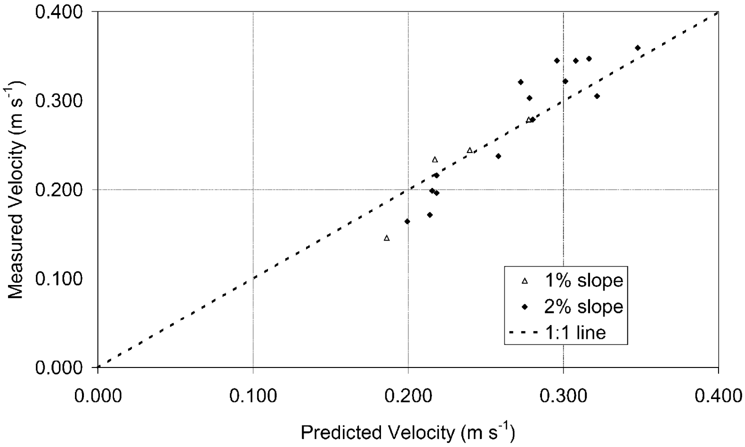

Fig. 7. Predicted mean velocity (Manning's equation) versus estimated mean velocity (measured leading edge velocity multiplied by correction factors proposed by Li et al. (1996)) for all rain impacted experiments.

Table 2
Parameter ranges of the sediment deposition data used for calibration and validation of the multi-class net deposition equation in the presence of rainfall (n_0 = number of experiments)

	n_0	Unit discharge ($m^2 s^{-1}$)	Slope ($m m^{-1}$)	Inflow sediment conc. ($kg m^{-3}$)	Material
Data used for calibration	10	0.00034–0.00138	0.02	59–167	Silty soil type B
Data used for evaluation	9	0.00045–0.00135	0.01–0.02	51–171	Silty soil type B

unimpacted flows there is no vertical sediment gradient in the sediment-laden shallow overland flow. Consequently, the α_i term is taken as unity in this study.

The inflow sediment-size distribution is divided into 10 size classes of equal mass. For each size class a characteristic settling velocity is calculated using the algorithm presented by Dietrich (1982) using the mean class size, a shape factor of 0.7 and a roundness value of 3.5.

The threshold value at which there is a sharp rise in sediment flux as measured by Beuselinck et al. (1999a) is used as critical stream power (Ω_0). We assume that rainfall impact has no effect on the threshold value. Below the threshold value, the model describes sediment transport by overland flow as the net outcome of simultaneous deposition at a rate proportional to the settling velocity of the classes and raindrop re-detachment of the deposit. At flow conditions above the threshold value, the model assumes that sediment deposition, flow re-entrainment and rain re-detachment occur simultaneously.

The optimised F-value (i.e. the fraction of the stream power available for sediment re-entrainment) obtained in the calibration run of the unimpacted net deposition equation (Beuselinck et al., 2001b) is used for the evaluation of the rain-impacted net deposition equation. Thus, it is assumed that raindrop impact does not affect the threshold value at which there is a sharp rise in transport capacity nor the fraction of the stream power available for re-entrainment.

Proffitt et al. (1991) experimentally determined a value of exponent p of 0.88. This value was obtained using two different soil types, three flow depths and two rainfall rates. Proffitt et al. (1991) assumed that p was unity in their determination of the detachability values, a and a_d, since standardisation of the exponent p simplifies the comparison of the susceptibilities of various soils to rain (re-)detachment. Therefore, in this study a p value of 1 is adopted. Based on the experimental work of Proffitt et al. (1991), D_0, the critical water depth up to which the detachability values are at their maximum is taken as 0.002 m. For flows deeper than this critical depth, the Hairsine–Rose model assumes that the relationship between flow depth and detachability can be described by a negative power function (Eq. (4)). The exponent b of this power function is assigned a value of -0.66 based on the same set of experiments carried out by Proffitt et al. (1991).

The susceptibility of the soil to rainfall re-detachment (a_{d0}) remains the only unknown in the net deposition algorithm for rain-impacted overland flow (Eq. (10)). Consequently, calibration is carried out by adjusting the a_{d0} value between 0 and 225 000 kg m^{-3}. If $a_{d0} = 0$, the deposited sediment is not susceptible to re-detachment. In these circumstances, the algorithm reduces to the simple settling theory at discharges below the threshold and to the solution for unimpacted flows for discharges above the threshold. If $a_{d0} = 225\,000$ kg m^{-3}, the algorithm predicts total sediment delivery for each experiment used in the calibration run.

6. Model testing

6.1. Model calibration and evaluation procedure

The rain-impacted sediment deposition dataset is divided into two subsets for calibration and evaluation of the model. Ten experiments conducted on a 2% slope are selected for calibration. Five experiments carried out on a 2% slope and four experiments conducted on a 1% slope are used for evaluation of the optimised model. Table 2 gives the parameter ranges for both experimental data sets.

The net deposition algorithm for rain-impacted flow was calibrated for a_{d0} by minimising the error in both the overall outflow sediment concentration

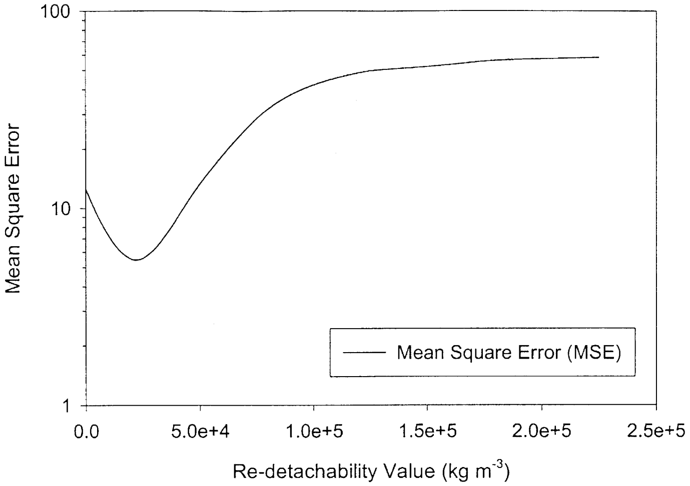

Fig. 8. Objective function of the residues (MSE) versus the re-detachability value.

and the settling velocity distribution of the exported sediment. The same statistical method as was used to calibrate the unimpacted net deposition theory (Beuselinck et al., 2001b) was used to calibrate the rain-impacted net deposition theory. This method minimises the error in both the total outflow sediment concentration and the settling velocity distribution of the exported sediment. The goodness of it was measured by the mean square error

$$\mathrm{MSE} = \frac{1}{n_0}\left[\sum_{j=1}^{n_0}\left(\sum_{i=1}^{10}\frac{(O_{ij}-P_{ij})^2}{O_{ij}}\right)\right] \tag{11}$$

where O is the observed outflow sediment concentration, P is the predicted outflow sediment concentration, n_0 is the number of experiments and the subscripts i and j denote the class number and experiment number, respectively.

The model was evaluated using the second subset of data by predicting total outflow and the settling velocity distribution of the delivered sediment using the optimised re-detachability value obtained in the calibration run.

6.2. Model calibration

Fig. 8 shows the objective function resulting from the calibration of the model. The best predictions for both the overall outflow sediment concentrations and for the settling velocity distribution of the exported sediment are obtained when using a detachability value of 22 500 kg m^{-3} (MSE = 5.5). If the raindrop impact is neglected (a_{d0} = 0 kg m^{-3}) a MSE value of 12.5 is obtained. Assuming, on the other hand, that all sediment is exported out of the flume (a_{d0} = 225 000 kg m^{-3}), results in a MSE of 58.3. Consequently, predictions of the overall outflow sediment concentration and of the settling-velocity distribution

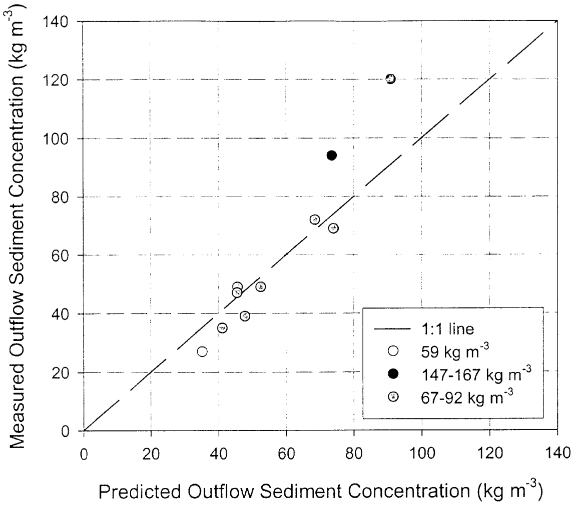

Fig. 9. Predicted versus measured overall sediment concentration using the optimised re-detachability value to predict the sediment deposition data used for calibration.

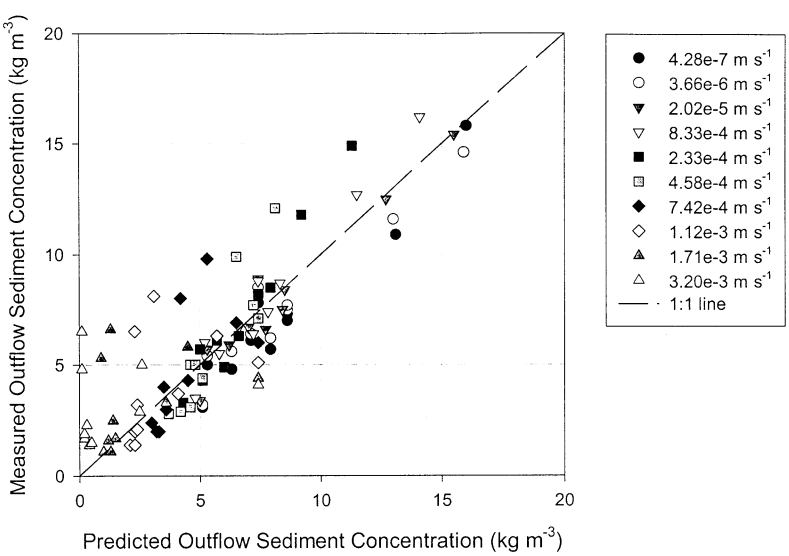

Fig. 10. Predicted versus measured sediment concentration for each of the 10 settling velocity classes using the optimised re-detachability value to predict the sediment deposition data used for calibration.

of the exported sediment can be improved by introduction of the rain re-detachment function if the appropriate parameter value for the re-detachability is used. The optimised re-detachability value of 22 500 kg m^{-3} corresponds with the re-detachability value obtained by Proffitt et al. (1991) for a weakly structured Aridisol. Proffitt et al. (1991) obtained a significantly lower re-detachability value for a well-aggregated Vertisol.

Fig. 9 shows the predicted versus the measured overall outflow sediment concentration for all experiments in the calibration run using the optimised re-detachability value. There is good agreement between predicted and measured outflow sediment concentrations for the experiments conducted with a low- and a medium-inflow sediment concentration. However, outflow sediment concentrations are underpredicted for the experiments carried out with a high-inflow sediment concentration. For most experiments, the model predicts reasonably well the outflow sediment concentration for each size class separately (Fig. 10). MSE's are highest for the coarsest size fractions (Table 3). However, for experiments conducted at a high inflow sediment concentration, outflow sediment concentrations are underpredicted for most size classes.

6.3. Model evaluation

For the experiments employed in the evaluation process the predicted outflow sediment concentrations using the optimised model are in agreement with the observed outflow sediment concentrations (Figs. 11 and 12). The MSE for the sediment deposition data selected for evaluation is significantly lower than the MSE obtained for the experiments used for calibration (Table 3). The optimised model also predicts well the sediment-size distribution of the exported sediment. The MSE is highest for the coarsest fraction (Table 3). The export of the coarsest material is underestimated by the model, whereas the export of fines is overestimated.

7. Discussion

Fig. 13 shows the predicted (optimised model) effect of the rainfall on SDR on 1 and 2% slopes. On the 1% slope flow re-entrainment is negligible at discharges below 0.002 m^2 s^{-1}. The predicted relative importance of the raindrop impact decreases slightly with increasing flow discharge. On the 2% slope the optimised solution predicts that the relative importance of raindrop impact is much smaller for

Table 3
Mean square error and mean absolute error for each settling velocity class and for the total outflow sediment concentration using the sediment deposition data selected for the calibration ($n_0 = 10$) and evaluation ($n_0 = 9$) of the multi-class net deposition equation in the presence of rainfall

	Class	1	2	3	4	5	6	7	8	9	10	Total
	Lower settling velocity	–	1.16×10^{-6}	1.81×10^{-5}	1.21×10^{-4}	3.24×10^{-4}	5.65×10^{-4}	8.50×10^{-4}	1.22×10^{-3}	1.77×10^{-3}	3.03×10^{-3}	
	Upper settling velocity	1.16×10^{-6}	1.81×10^{-5}	1.21×10^{-4}	3.24×10^{-4}	5.65×10^{-4}	8.50×10^{-4}	1.22×10^{-3}	1.77×10^{-3}	3.03×10^{-3}	1.10×10^{-2}	
Calibration	MSE	0.35	0.22	0.13	0.12	0.22	0.38	0.56	0.73	1.00	1.89	1.65
	MAE	0.20	0.15	0.10	0.11	0.15	0.21	0.28	0.32	0.34	0.68	0.13
Validation	MSE	0.35	0.32	0.16	0.05	0.08	0.15	0.21	0.21	0.25	0.75	0.67
	MAE	0.16	0.13	0.09	0.06	0.07	0.12	0.17	0.19	0.24	0.45	0.08

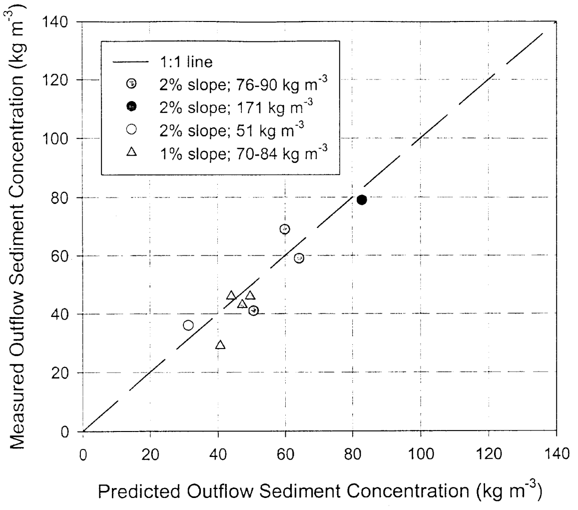

Fig. 11. Predicted versus measured overall sediment concentration using the optimised re-detachability value to predict the sediment deposition data used for validation.

conditions where sediment re-entrainment is significant than for discharges where sediment re-entrainment is negligible, as was experimentally observed. For discharges below the threshold value for flow re-entrainment, rain re-detachment is slightly more important on the 2% slope than at the 1% slope. A comparison of Figs. 6 and 13 reveals that the optimised model predicts well the effect of raindrop impact on SDR as discharge increases.

Comparison of the experimental data with the predictions of the multi-class solution indicates that the optimised model predicts well the effect of variations in slope and unit discharge on rain-impacted sediment deposition. This confirms that the slope dependence of rainfall re-detachment results from slope steepness affecting flow depth and flow velocity. Furthermore, it illustrates that the decline in rain re-detachment at increasing flow depth, resulting from an increase in flow discharge, is partially offset by the more efficient export of detached sediment at higher flow rates. The model is unable to predict accurately the effect of changes in inflow sediment concentration on SDR in the presence of rainfall. The optimised re-detachability value seems to increase with increasing inflow sediment concentration. This can be explained by the simplifications made when developing the theory, as was described by Beuselinck et al. (2001a,b). In developing the multi-class model normal flow conditions were assumed. However, the steeper lead-in flume causes transitional flow hydraulics in the beginning of the depositional flume. These non-normal flow conditions have an impact on the decline in sediment concentration down-flume.

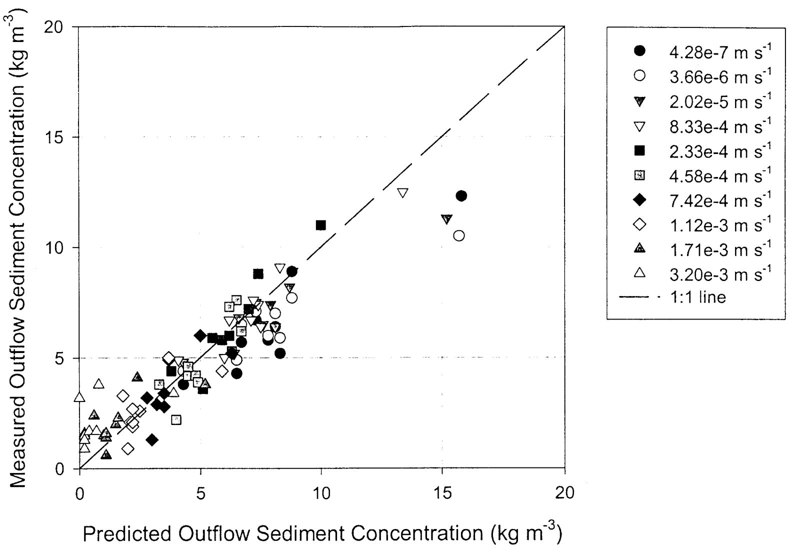

Fig. 12. Predicted versus measured sediment concentration for each of the 10 settling velocity class using the optimised re-detachability value to predict the sediment deposition data used for validation.

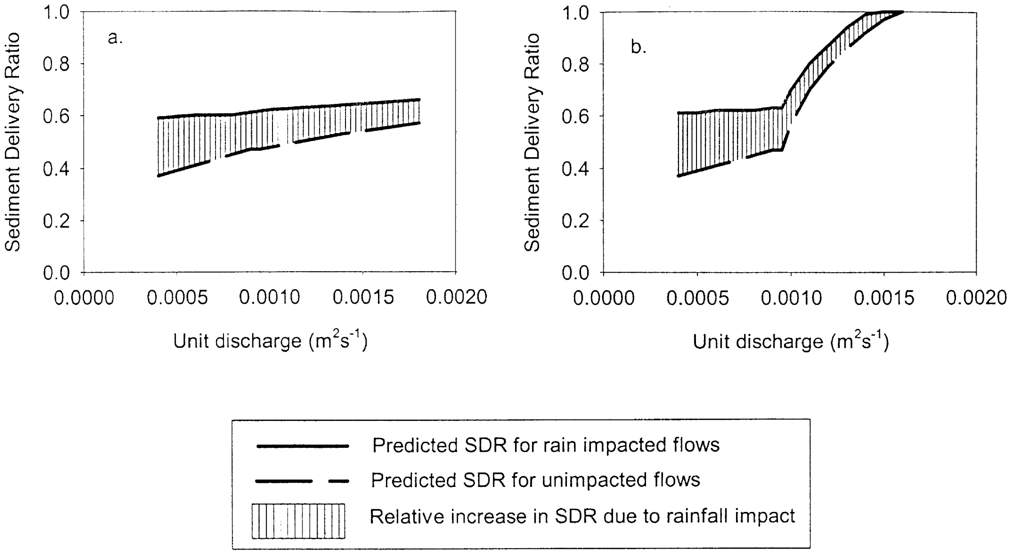

Fig. 13. Predicted relative effect of rainfall re-detachment on the SDR versus unit discharge on (a) a 1% and (b) a 2% slope ($c_{in} = 80$ kg m^{-3}, Sed. type B); Threshold for re-entrainment is at 0.002 m^2 s^{-1} and at 0.00095 m^2 s^{-1} for, respectively, a 1 and 2% slope.

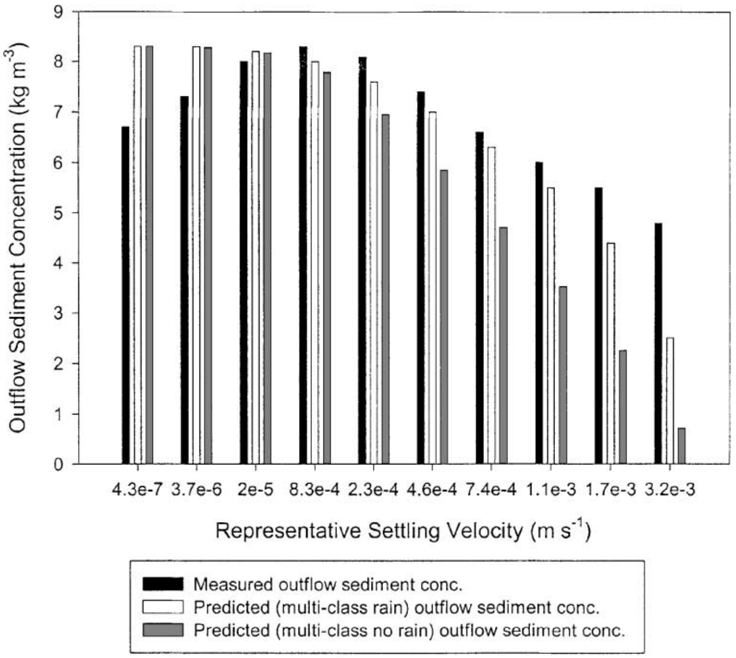

Fig. 14. Predicted (model predictions in presence/absence of rainfall) versus measured outflow sediment concentration for each settling velocity class for an experiment used in the validation process ($q = 0.00083$ m^2 s^{-1}; $c_{in} = 43$ kg m^{-3}).

The Hairsine–Rose theory model assumes that raindrop impact detaches sediment non-selectively from the previously deposited mass, which is much coarser than the inflow sediment. This re-detached sediment is partially re-deposited as a result of the trajectories of widely varying lengths. Consequently, the model predicts that part of this mainly coarse sediment, which would be deposited in the absence of rainfall, is exported out of the flume due to rain re-detachment. Also for discharges at which sediment re-entrainment is significant, rain re-detachment results in additional export of coarse particles. If rainfall re-detachment is neglected in the predictions of the outflow sediment concentrations, the predicted outflow size distribution is finer than the observed size distribution. Using the optimised detachability value significantly improves the prediction of the outflow sediment concentration for each settling velocity class, as is illustrated in Fig. 14. Comparison of predicted and observed outflow sediment concentrations for each settling velocity class shows that the assumption of non-selective re-detachment, non-selective re-entrainment and size-selective deposition predicts reasonably well the size selectivity of the net deposition process (Figs. 10 and 12). The term $M_{\mathrm{d}i}/M_{\mathrm{dt}}$ incorporated in the Hairsine–Rose model to describe the non-selective re-detachment is thus a valuable term to predict the size-selectivity of the deposition process in the presence of rainfall.

The multi-class solution for the Hairsine et al. (2001) rain-impacted net deposition equation underpredicts the export of the coarsest settling velocity class and slightly overpredicts export of fines. The same discrepancies were observed when predicting sediment export in the absence of rainfall (Beuselinck et al., 1999b, 2001b). Underestimation of the coarsest sediment fraction is explained by bedload transport processes (Beuselinck et al. 1999b). The overpredicted export of fines is attributed to the trapping of fines in the wake of coarser particles. Both processes are not incorporated in the Hairsine–Rose model.

The equation describing raindrop impact in the Hairsine–Rose model (Hairsine and Rose, 1991; Eq. (2)) is similar to the equation incorporated in the EUROSEM model (Morgan et al., 1998). In both equations, sediment detachment by raindrop impact depends on an erosivity parameter (i.e. rain intensity in the Hairsine–Rose model, kinetic energy in the EUROSEM model), on the detachability of the sediment, and on the depth of water covering the source sediment. The main difference between these models is that the EUROSEM equation uses a single characteristic sediment size class, whereas the Hairsine–Rose equation is a multi-class equation. The main advantage of the latter model is that it can give information on sediment sorting and, hence, on the related chemical sediment quality.

There is still discussion about which rain erosivity parameter can best be used to predict soil detachment by splash (Salles and Poesen, 2000). Some authors use a power function of the rainfall intensity to predict the effect of raindrop impact on soil detachment (e.g. Smith and Wishmeier, 1957; Govers, 1991; Nearing et al., 1989; Hairsine and Rose, 1991; Eq. (3)). Others use a function of the kinetic energy (e.g. Young and Wiersma, 1973; Quansah, 1981; Poesen, 1985; Morgan et al., 1998; Eq. (5)) or of the rainfall momentum (e.g. Park et al., 1983; Schmidt, 1991). Salles and Poesen (2000) and Salles et al. (2000) compared these different erosivity parameters and concluded that rainfall momentum multiplied by the raindrop diameter is the most suitable parameter to predict soil detachment by splash in the absence of overland flow. An additional advantage of the using kinetic energy or momentum of the rain is that these erosivity parameters are capable of taking into account the effect of a vegetation canopy on sediment detachment by raindrop impact (Brandt, 1988). Larger drop sizes from leaf drip (Salles and Poesen, 2000) and lower fall velocities (Young and Wiersma, 1973) influence the rainfall kinetic energy and the momentum of the rain, whereas the overall rainfall intensity remains constant. However, Moss and Green (1983) show that no simple relationship can exist between kinetic energy and rain-flow transportation. Kinnell (1991) also states that kinetic energy is not a good predictor of rain-impacted sediment transport by overland flow due to the interactions of drop and flow energy. Walker et al. (1978) found that sediment flux due to raindrop impact on overland flow is closely related to rainfall intensity. Further research should focus on which erosivity parameter best predicts rain detachment in the presence of a water layer covering the source material. The best parameter could be simply incorporated in the presented model.

8. Conclusions

Rainfall affects both overland flow hydraulics and sediment transport. In this experiments, only limited surface flow retardation due to raindrop impact was measured. This is probably due to the low rainfall intensity and the small median raindrop size used in the experiments. A reduction in flow velocity has negative consequences for sediment delivery. Due to the flow retardation, the suspended sediment is less efficiently transported over the area of net deposition. Additionally, flow depth increases. As a result the efficiency of raindrop re-detachment also diminishes.

The negative effect of flow retardation on sediment transport by rain-impacted overland flow is overwhelmed by the positive effect due to rain re-detachment of previously deposited sediment. The experimental results clearly show the increase in sediment delivery due to raindrop impact. In the presence of rainfall, significantly more coarse material is exported out of the flume. Raindrop impact re-detaches sediment from the previously formed deposit. This sediment is then transported by the flow, settling at a rate proportional to the sediment's fall velocity. Deposited sediment may subsequently be re-detached by the raindrop impact. Consequently, the observed increase in SDR is caused by re-detachment introducing more sediment into the flow.

Comparison of the experimental data collected under rainfall conditions with the multi-class model (Hairsine et al., 2001; Sander et al., 2001) showed that the solution predicts reasonably well the overall sediment delivery and the sediment sorting during sediment transport over areas of net deposition. The impact of changes in slope and in unit discharge on rain re-detachment in conditions where sediment deposition may occur are well described by the model.

As observed in the experimental data, the theory predicts that considerable amounts of coarse sediment, which would be deposited in the absence of rainfall, are transported over an area of net deposition due to rainfall impact. These results indicate that the physical approach of non-selective re-detachment and size-selective sediment re-deposition used in the Hairsine–Rose model does accurately describe the impact of rainfall on the size selectivity of the deposition process.

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