Simulations demonstrating interaction between coarse and fine sediment loads in rain-impacted flow

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Abstract

Rain-impacted flows dominate sheet and interrill erosion and are important in eroding soil rich in nutrients and other chemicals which may have deleterious effects on water quality. Erosion in rain-impacted flow is associated with raindrop detachment followed by transport either by the combination of flow velocity and raindrop impact (raindrop-induced flow transport, RIFT) or the inherent capacity of the flow to transport detached material. Coarse particles tend to be transported by RIFT, while fine particles tend to be transported without any assistance from raindrop impact. Because the transport process associated with coarse particles is not 100 per cent efficient, it generates a layer of loose particles on the soil surface and this layer protects the underlying soil from detachment. Simulations were performed by modelling the uplift and downstream movement of both fine and coarse particles detached from the soil surface by individual raindrop impacts starting with a surface where no loose material was present. The simulations produced a flush of fine material followed by a decline in the discharge of fine material as the amount of loose material built up on the bed. The decline in the discharge of fine material was accompanied by an increase in the discharge of coarse material. The relative amounts of coarse and fine material discharged in the flow varied with flow velocity and cohesion in the surface of the soil matrix. The results indicate that the discharge of various sized sediments is highly dependent on local soil, rain and flow conditions and that extrapolating the results from one situation to another may not be appropriate. Copyright © 2006 John Wiley & Sons, Ltd.

Keywords: rainfall erosion; particle size; cohesive surfaces

Introduction

Four detachment and transport systems operate in rainfall erosion (Kinnell, 2001).

1. Raindrop detachment–splash transport (RD-ST). RD-ST is common in sheet and interrill areas prior to the development of runoff. Splash transport is highly dependent on slope gradient and decreases rapidly as the depth of water on the surface increases (Moss and Green, 1983). RD-ST is a transport-limited system, particularly when operating on large areas.

2. Raindrop detachment–raindrop-induced flow transport (RD-RIFT). RD-RIFT occurs in rain-impacted flow when flow shear stress or stream power is not only insufficient to detach soil material from the surface of the soil mass but also insufficient to entrain loose soil material sitting on top of the soil surface. In RIFT, sediment transport is induced by raindrop impact lifting the loose material up into the flow and will not occur in the absence of either raindrop impact or flow (Kinnell, 1990, 1993a; Moss and Green, 1983). RD-RIFT is a transport-limited system where the transport efficiency varies with flow velocity (Kinnell, 1994).

3. Raindrop detachment–flow transport (RD-FT). RD-FT occurs in rain-impacted flow when cohesion in the soil surface is high enough to prevent detachment by flow but not sufficient to prevent detachment by raindrops impacting the flow, and the flow shear stress or stream power is sufficient to transport detached material. RD-FT is a detachment-limited erosion system. It is well known that the critical hydraulic conditions required to initiate motion of loose particles sitting on the bed under undisturbed shallow flow varies with particle size and density. Consequently, RD-FT can operate simultaneously with RD-RIFT when raindrops impact flows over soil material having a wide range of particle sizes (Kinnell, 2001).
Figure 1. Detachment and transport processes associated with variations in raindrop and flow energies: $e_c$ = critical raindrop energy to cause detachment – raindrop-induced erosion occurs when drop energy exceeds $e_c$; A = line for $e_c$ when raindrops are detaching soil particles from the soil surface prior to flow development – the slope on this line is used to indicate increasing resistance to detachment caused by, for example, crust development; B = line for $e_c$ when raindrops are detaching soil particles from the soil surface when flow has developed – the slope on this line is used to indicate increasing utilization of raindrop energy in penetrating the flow when flow depth increases as stream power increases; $\omega_{CT}$ = critical stream power required to transport loose (previously detached) soil particles; $\omega_{CD}$ = critical stream power required to detach particles bound within the soil surface (held by cohesion and inter-particle friction); RD-ST = raindrop detachment–splash transport; RD-RIFT = raindrop detachment–raindrop-induced flow transport; RD-FT = raindrop detachment–flow transport; FD-FT = flow detachment–flow transport.

4. Flow detachment–flow transport (FD-FT). FD-FT is normally associated with erosion in rills, but has been observed in sheet flow on high strength crusted surfaces (Romkens, personal communication). On less stable surfaces, FD-FT leads to the development of micro-rills in interrill areas (e.g. in experiments by JM Meyer and Harmon, 1989).

Figure 1 indicates the domains for these four detachment and transport system with respect to variations in rain and flow energetics represented by raindrop kinetic energy and stream power.

Rain-impacted flows dominate sheet and interrill erosion and are important in eroding soil rich in nutrients and other chemicals which may have deleterious effects on water quality. Erosion by rain-impacted flow has dominated a large number of laboratory and field experiments. RD-RIFT and RD-FT are the dominant detachment and transport systems operating in rain-impacted flows. Rose et al. (1983) proposed a mathematical framework for modelling rainfall erosion based on the concept that mass conservation of sediment of size class $i$ requires that

$$\frac{\partial}{\partial x}(q_x c_i) + \frac{\partial}{\partial t}(hc_i) = r_i - d_i + f_i$$

where $h$ is flow depth, $r$ is the rate of rainfall detachment, $d$ is the sediment deposition rate and $f$ is the sediment entrainment rate. For bare soil surfaces, they proposed that

$$r_i = aC_p i^p N^{-1}$$

where $a$ is a soil-related coefficient, $C_p$ is the fraction of the soil that is unprotected, $p$ is an exponent originally thought to be close to 2 but now considered to be approximately 1 (Proffitt et al., 1991) and $N$ is the number of sediment size classes being considered. $N$ appears in Equation 2 as a result of the stipulation that $c_i = cN^{-1}$. In terms of Equation 1

$$d_i = aN^p c_i$$
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Figure 2. Diagrammatic representation of particle uplift and travel associated with fine and coarse particles in rain-impacted flows on slopes of low gradient.

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where \( v_{pi} \) is the mean settling velocity in water of particles in size class \( i \), \( \alpha_i \) is the sediment concentration close to the bed, and \( c_i \) is the depth-averaged sediment concentration (Hairsine and Rose, 1991). For erosion by rain-impacted flow on low slope gradients \( f_i \) is usually zero. According to Rose et al. (1983), the steady-state solution for \( c_i \) in the ordinary differential equations that result from Equations 1 to 3 and \( f_i = 0 \) is

\[
c_i = \frac{aC_i I^n}{N(q'_w + v_{pi})} \tag{4}
\]

where \( q'_w \) is the water discharged per unit area. The effect of \( q'_w \) in Equation 4 is not in any way associated with the effect of flow depth on sediment concentration that results from the dissipation of raindrop kinetic energy in the water flow. That is dealt with through the term \( a \) (Rose and Hairsine, 1988; Hairsine and Rose, 1991). It simply results from the solution to the differential equations that result from Equations 1 to 3 and, according to Rose et al. (1983) the effect of \( q'_w \) is frequently extremely small because often \( v_i >> q'_w \).

As a general rule, fine particles are associated with RD-FT while coarse particles are associated with RD-RIFT. Figure 2 provides a diagrammatic representation of the uplift and travel vectors for coarse particles associated with RD-RIFT and fine particles associated with RD-FT in rain-impacted flow. Fine particles remain suspended and move downstream without any further stimulation from raindrop impact. Coarse particles fall back to the bed within limited distances of the point of drop impact and have to wait for a subsequent raindrop impact before moving further downstream. The contribution of previously detached material to the discharge of sediment in the Hairsine and Rose (1991) approach is represented diagrammatically in Figure 3. The previously detached material deposited on the bed provides a degree of protection to the detachment of particles from within the surface of the soil matrix and is represented mathematically through

\[
a = (1 - H_k)a_M + H_k a_{PD} \tag{5}
\]

where \( a_{PD} \) is the value of \( a \) when the layer of previously detached material completely protects the underlying surface against detachment (\( H_k = 1 \)) and \( a_M \) is the value of \( a \) when there is no previously detached material on the soil surface (\( H_k = 0 \)). According to Hairsine et al. (1999), for shallow rain-impacted flows where \( f_i = 0 \) and \( \alpha = 1 \), the time-varying solutions to

\[
\frac{\partial}{\partial x} (q_w c_i) + \frac{\partial}{\partial t} (h c_i) = \frac{a_M I}{N} (1 - H_k) + a_{PD} H_k - v_i c_i \tag{6}
\]

such as those developed by Sander et al. (1996) are both complex and computationally demanding. Steady-state solutions, such as those developed by Hairsine and Rose (1991), are less demanding. Recently, Hogarth et al. (2004a, b) developed new time-varying numerical and analytical solutions for Equation 6.
An alternative approach to modelling erosion by rain-impacted flow results from experiments reported by Kinnell (1990). Kinnell observed that when coarse particles are lifted into the flow and fall back to the bed, the discharge of sediment across any arbitrary boundary is controlled by the impacts of drops within a limited distance of that boundary. The distance $X_{p,d}$ that a particle of effective size $p$ (the size of a sand particle having the same settling velocity as the particle of interest) travels after being disturbed by the impact of a drop of size $d$ determines the upslope limit of the zone in which such impacts occur. If $M_{p,d}$ is the mass of $p$ sized material lifted into the flow by a drop of size $d$, then

$$q_s(p,d) = M_{p,d} F_d X_{p,d}$$

where $q_s(p,d)$ is the mass of sediment of size $p$ discharged per unit width of flow in unit time (g m$^{-1}$ s$^{-1}$) and $F_d$ is the spatially averaged frequency of the impacts of drops of size $d$ (number of drops m$^{-2}$ s$^{-1}$) in the zone that extends the distance $X_{p,d}$ (m) upslope of the boundary. Initially there may be no previously detached particles sitting on the surface but impacts upstream of the zone move previously detached material into the zone to be subsequently discharged across the boundary. Consequently, if $M_{p,d,M}$ is the mass of $p$ sized material lifted into the flow when no previously detached particles are present ($H_R = 0$) and $M_{p,d,PDL}$ is the mass of $p$ sized material lifted into the flow when the layer of previously detached particles completely protects the underlying soil surface from detachment ($H_R = 1$), the value of $M_{p,d}$ at any time is given by (Kinnell, 1993b)

$$M_{p,d} = M_{p,d,M}(1 - H_R) + H_R M_{p,d,PDL}$$

This equation gives $M_{p,d,M}$ when $H_R = 0$ and $M_{p,d,PDL}$ when $H_R = 1$ and a linear transition between these two values as $H_R$ varies between 0 and 1. Combining Equations 7 and 8 gives

$$q_s(p,d) = (M_{p,d,M}(1 - H_R) + H_R M_{p,d,PDL}) F_d X_{p,d}$$

The deposited layer is dynamic in composition. It varies in time and space depending on flow velocity ($u$) and particle settling velocity ($v_p$). Figure 4 provides a diagrammatic representation of how particles of varying settling velocity contribute to the mass of deposited material sitting on the bed, assuming that the sediment is distributed uniformly through the flow upon entering the segment. Given values of $M_{p,d,M}$, $M_{p,d,PDL}$, $H_R$, $F_d$ and $X_{p,d}$ in the area immediately upstream of the segment, $q_d$ can be determined from Equation 9 and the approach illustrated in Figure 4 used to determine the composition and protective effect of the deposited layer in the segment. The sediment discharge from the segment ($q_{so}$) associated with subsequent drop impacts can then be calculated using Equation 9 in a mass balance approach that takes account of the mass conservation of sediment in the deposited layer (Kinnell, 1994). The approach has the capacity to deal with the discharge of both coarse and fine particles since the fine particles do not settle back to the bed within the segment and pass straight through.
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Figure 4. Schematic diagram of travel during deposition of the smallest (b) and largest (a) non-suspended-load soil particles entering an element of flow during RIFT (after Kinnell, 1994). The solid arrowed lines that originate at the top of the water surface show the directions in which particles of size a and b fall assuming that the horizontal vector is directly related to flow velocity (u) and the vertical vector is directly related to the particle settling velocity (v_p). x_p(a) and x_p(b) are the distances particles of size a and b originating at the water surface travel during their fall. Once deposited on the bed, Equation 9 can be applied to determine the contribution of the deposited material to the discharge of sediment (q_so) across the downstream boundary of the segment. d_x = length of the element; q_in = sediment discharge entering the element; q_so = sediment discharge from the element; ZD(a) = depth of material with particle size a deposited on the surface; ZD(b) = depth of material with particle size b deposited on the surface.

Figure 5. Schematic representation of particle uplift and fall associated with raindrop-induced flow transport (RIFT) in the simulations undertaken by Kinnell (1994). The parameter values shown were used in the simulations undertaken by Kinnell (1994).

Although Equation 9 can be applied in the mass balance approach considered above, it also provides a basis for simulating the effect of the movement of coarse material associated with individual drop impacts. Kinnell (1994) used a random number generator to determine the position of drop impacts on a 250 mm long cohesive surface and moved a rectangular cloud downstream a distance that varied with flow velocity before depositing the particles in the cloud onto the bed. The approach used is shown diagrammatically in Figure 5. Kinnell (1994) used a single particle size and confined his observations to variations in long-term values of H_R over the length of the eroding surface in response to changes in flow velocity and the cohesiveness of the eroding surface. No attempt was made to model q_(p,d) or provide data on how H_R varied temporally. In this paper, the approach is used to model sediment discharges from a surface containing two particle sizes (one coarse associated with RD-RIFT, one fine associated with RD-FT) and to illustrate how H_R varies in both time and space. Although the simulations do not include the effect of particle size on the composition of the layer of previously detached particles, they do demonstrate how coarse material influences the discharge of fine material.
The Simulation Model

Kinnell and McLachlan (1989) undertook experiments with blocks of soil 500 mm long and 250 mm wide under flows of uniform depth of between 3 and 8 mm, impacted by rain of intensity 64 mm h\(^{-1}\) rain and drop size 2-7 mm travelling at near-terminal velocity. The simulations reported here involve modelling the uplift and downstream movement of particles resulting from individual drop impacts associated with 60 mm h\(^{-1}\) uniform-sized rain (2-7 mm drops) on a 200 mm wide, 500 mm long surface covered by flow with a uniform depth (7 mm) and velocity (\(u\)) over a period of 5 min. In the simulations, each drop impact disturbed a 5 mm by 5 mm (25 mm\(^2\)) area of the bed. A square rather than round disturbed area was used for simplicity. The size of the disturbed area was based on the fact that a drop impact produces a crater whose maximum depth is 3d (Engel, 1966). Consequently, an area of about 5 mm in diameter will be disturbed when 2-7 mm drops impact flows that are 7 mm deep. As with the simulation undertaken by Kinnell (1994), the position of the drop impacts was random to the extent that it was chosen using a computer-based random number generator. The impact positions were constrained within the 500 mm by 200 mm area in such a way that no impact disturbed less than the 5 mm by 5 mm area of the bed. With 2-7 mm drops and a rainfall intensity of 60 mm h\(^{-1}\), 156 drops impacted the surface in each second. Simulations were performed over a range of flow velocities (10 mm s\(^{-1}\) to 100 mm s\(^{-1}\)).

As in the Kinnell and McLachlan (1989) experiments, clean water enters the test area from upslope and, for simplicity, the raindrops impacting in the test area did not contribute to the flow. When no protection was provided by previously detached particles, each drop impact lifted an arbitrary 0.5 mg of fine material into a cloud that had an 11 mm by 11 mm (121 mm\(^2\)) horizontally projected area. The size of the cloud was arbitrary and compares with the 18 mm by 18 mm (324 mm\(^2\)) projected area used by Kinnell (1994) for a 5 mm drop impacting a 5 mm deep flow. The detached material was distributed uniformly through the cloud. However, as the fine particles do not return to the bed, how the particles were distributed vertically had no impact on sediment discharge. The fine particles lifted into the flow were added to those already in the flow and moved horizontally at the velocity of the flow (\(u\)). The actual size of the fine particles was immaterial to the simulation.

In the simulations, coarse particles lifted into the flow travel a distance of 0.2\(u\) before being returned to the bed. This distance is associated with 0-46 mm sand and 2-7 mm drops. Kinnell (2001) observed that the effective average distance travelled by 0-46 mm particles of sand in experiments with 2-7 mm drops impacting flows 7 mm deep, was 7.5 mm when the flow velocity was 40 mm s\(^{-1}\). The value 0.2\(u\) for \(u = 40 \text{ mm s}^{-1}\) gives a distance of 8 mm. Applying Equation 7 to data from the experiments with 0-46 mm sand and 2-7 mm drops gives \(M_{p,d} = 10 \text{ mg}\) when \(H_k = 1\). The average steady-state discharge is 7 mm deep. A value of 10 mg was used in the simulations. An arbitrary value of 2 mg was selected for \(M_{p,d}\) when \(H_k = 0\). As with the fine material, the coarse particles were distributed uniformly through the cloud but no account was taken of how the particles were distributed vertically in the flow. This resulted in the deposit having sharp edges in the downstream direction whereas, in reality, these edges should be somewhat diffuse. While this difference had some impact on the results, it was probably small. In addition to simulations associated with fine and coarse particles in rain-impacted flows over a cohesive surface, simulations were performed with surfaces made up of entirely coarse or fine particles to demonstrate the discharges of coarse and fine particles without any interaction between them.

Results

Figure 6 shows sediment discharges at 1 second intervals for simulations with surfaces made up entirely of fine material and flow velocities of 10 mm s\(^{-1}\) and 100 mm s\(^{-1}\). In both cases, sediment discharges reached the same average steady-state discharge (0-40 g m\(^{-1}\) s\(^{-1}\)). A total of 780 drop impacts will occur on a 500 mm long, 1000 mm wide surface in each second when subjected to rain of intensity 60 mm h\(^{-1}\) made up entirely of 2-7 mm drops so that, with 0.5 mg per impact, the theoretical steady-state discharge is 0-39 g m\(^{-1}\) s\(^{-1}\). The average steady-state discharges were achieved at times consistent with the time taken for a particle to travel from the most upstream point on the eroding area to the downstream boundary (50 s for 10 mm s\(^{-1}\), 5 s for 100 mm s\(^{-1}\)). The results are consistent with erosion taking place where transport is not a limiting factor.

It should be noted that the discharge of fine particles continues after the cessation of rain for a time depending on the time taken for a fine particle to travel from the most upstream point on the eroding area to the downstream boundary when the flow of water is maintained. The after-rain discharge of fine particles is not shown in the data presented here although the model can simulate it.

Figure 7 shows sediment discharges at 1 second intervals for simulations with surfaces made up entirely of loose coarse material and flow velocities of 10 mm s\(^{-1}\) and 100 mm s\(^{-1}\). In this case \(H_k = 1\) occurs for each drop impact and...
the average steady-state discharge was obtained immediately. In contrast to the discharge of fine material, the average steady-state discharge varied with flow velocity ($u$). There is considerable short-term variation in the sediment discharges shown in Figure 7 at both flow velocities. While there are 156 drop impacts per second on the 500 mm by 200 mm surface, the discharge of sediment is controlled by the impacts in the zone immediately upstream of the downstream boundary and the upstream extent of this zone varies with flow velocity. For $u = 100 \text{ mm s}^{-1}$, the mean number of drops controlling the discharge of coarse sediment in 1 second is 7.14. However, because the drops fall randomly over the 500 mm by 200 mm area, there is considerably variation about this mean. The maximum and minimum numbers of drops controlling the discharge of the coarse sediment are 15 and 1 respectively, and the coefficient of variation is 36.8 per cent when $u = 100 \text{ mm s}^{-1}$. For $u = 10 \text{ mm s}^{-1}$, the mean number of drops controlling the discharge of coarse sediment in 1 second is 1.50. The maximum and minimum numbers are 7 and 0 respectively and the coefficient of variation is 81.7 per cent.

The effect of flow velocity on the average steady-state discharge is shown in Figure 8. A sediment discharge greater than zero occurred when flow velocity was zero because the part of the cloud associated with drop impacts immediately upstream of the downstream boundary extended beyond the downstream boundary. Whenever the flow velocity was less than 40 mm s$^{-1}$, part of the cloud with drop impacts immediately upstream of the downstream boundary fell

**Figure 6.** Sediment discharge of fine particles simulated for a 7 mm deep flow over a cohesive soil surface when flow velocity ($u$) equalled either 10 mm s$^{-1}$ or 100 mm s$^{-1}$ and no coarse particles are present in the surface of the soil.

**Figure 7.** Sediment discharge of coarse particles simulated for a 7 mm deep flow over a non-cohesive soil surface when flow velocity ($u$) equalled either 10 mm s$^{-1}$ or 100 mm s$^{-1}$. 

The average steady-state discharge was obtained immediately. In contrast to the discharge of fine material, the average steady-state discharge varied with flow velocity ($u$). There is considerable short-term variation in the sediment discharges shown in Figure 7 at both flow velocities. While there are 156 drop impacts per second on the 500 mm by 200 mm surface, the discharge of sediment is controlled by the impacts in the zone immediately upstream of the downstream boundary and the upstream extent of this zone varies with flow velocity. For $u = 100 \text{ mm s}^{-1}$, the mean number of drops controlling the discharge of coarse sediment in 1 second is 7.14. However, because the drops fall randomly over the 500 mm by 200 mm area, there is considerably variation about this mean. The maximum and minimum numbers of drops controlling the discharge of the coarse sediment are 15 and 1 respectively, and the coefficient of variation is 36.8 per cent when $u = 100 \text{ mm s}^{-1}$. For $u = 10 \text{ mm s}^{-1}$, the mean number of drops controlling the discharge of coarse sediment in 1 second is 1.50. The maximum and minimum numbers are 7 and 0 respectively and the coefficient of variation is 81.7 per cent.

The effect of flow velocity on the average steady-state discharge is shown in Figure 8. A sediment discharge greater than zero occurred when flow velocity was zero because the part of the cloud associated with drop impacts immediately upstream of the downstream boundary extended beyond the downstream boundary. Whenever the flow velocity was less than 40 mm s$^{-1}$, part of the cloud with drop impacts immediately upstream of the downstream boundary fell
back to the bed rather than passing over the boundary. This resulted in non-linearity in the relationship between the average sediment discharge and flow velocity when flow velocity was less than 40 mm s$^{-1}$. The relationship became linear when flow velocity exceeded 40 mm s$^{-1}$. In contrast to the discharge of fine particles, coarse particles are not discharged after the cessation of rain.

Figure 9 shows the discharges of fine and coarse particles at 1 second intervals for simulations with cohesive surfaces made containing both fine and coarse particles. Figure 10 shows how $H_R$, the ratio of the amount of previously detached particles sitting on the surface to the amount producing $H_R=1$, varies in the downstream direction.

$$H_R = H_Z \quad \text{for } H_Z < 1 \quad (10a)$$

$$H_R = 1 \quad \text{for } H_Z \geq 1 \quad (10b)$$

Thus, Figure 10A shows that spatial variation in $H_R$ was small when the flow velocity was 10 mm s$^{-1}$ but there was an increase in $H_R$ with distance from the upsource boundary as time increased when the flow velocity was 100 mm s$^{-1}$ (Figure 10B). The temporal increase in $H_R$ resulted in the discharge of coarse material gradually increasing with time. In the case of fine particles, the discharge initially increased towards the steady state values observed when no coarse particles were present (Figure 9) but then declined as the protective effect of the coarse particles sitting on the surface increased with time. The overall effect was for the total sediment discharge to peak and then fall when the flow velocity was 10 mm s$^{-1}$ (Figure 11). However, when the flow was 100 mm s$^{-1}$, the temporal fall in the discharge of fine particles was offset by the rise in the discharge of coarse sediment. The effect of flow velocity on the discharges of the sediments during the 4th minute is shown in Figure 12. As can be seen from Figure 12, the increase in sediment discharge during the 4th minute associated with the increase in flow velocity was largely caused by the increase in the discharge of the coarse sediment.

**Discussion**

Although the value for $M_{p,d}$ when $H_R=1$ used in the simulations came from experiments with 2.7 mm drops impacting flows over 0-46 mm sand, many of the other parameter values were chosen arbitrarily. Consequently, the results presented here are qualitative rather than quantitative. Considerable variation about average sediment discharges occur in the data for sediment discharges of coarse particles in 1 second intervals. This variation results from the relatively small number of drop impacts that occur on the surface in 1 second and the random distribution of the impact positions. This variation can be reduced by selecting a longer time interval, but the time interval of 1 second is appropriate with regard to determining the variation in sediment discharge of fine particles.

The simulations relate to the operation of RD-RIFT and RD-FT detachment and transport systems in rain-impacted flow. When the RD-FT system acts alone, erosion is detachment- rather than transport-limited and consequently, as
Figure 9. Sediment discharges of coarse and fine particles simulated for a 7 mm deep flow over a cohesive soil surface when flow velocity ($u$) equalled (A) $10 \text{ mm s}^{-1}$ and (B) $100 \text{ mm s}^{-1}$.

illustrated by the results presented in Figure 5, average sediment discharges are not influenced by flow velocity. When the RD-FT system operates in conjunction with the RD-RIFT system, the detachment of fine particles is controlled by the protective effect of the particles being transported by RIFT. It is because of this that the discharge of fine sediment falls with time of exposure to rainfall (Figure 9).

The values of $H_d$ shown in Figure 10 show that the build-up of loose material towards the downstream end when the flow velocity is $100 \text{ mm s}^{-1}$ can lead to areas where the layer of loose material completely protects the underlying soil surface. RIFT is a ‘bucket-brigade’ system and the efficiency of this transport system depends on the impacts that subsequently occur in the downstream direction. Failure to clear the particles at the same rate as they arrive leads to a build-up of the layer of loose particles. With the probability of an impact occurring at any given point not varying as flow velocity increases, the maximum possible clearance rate at any point downstream remains the same but, as flow velocity increases, the rate at which the loose particles arrive at that downstream point increases. This rate is greater than the maximum possible clearance rate in the lower part of the 500 mm long surface when the flow velocity is $100 \text{ mm s}^{-1}$. A reduction in $M_{p,d}$ for the coarse particles when $H_R = 0$ changes the balance between the rate of arrival
Figure 10. Average values of $H_Z$, the ratio of the amount of previously detached particles sitting on the surface to the amount producing $H_R = 1$, for 20 mm strips at various distances along the eroding surface observed at 1 minute intervals for the simulations for a 7 mm deep flow over a cohesive soil surface when flow velocity ($u$) equalled (A) 10 mm s$^{-1}$ and (B) 100 mm s$^{-1}$.

Figure 11. Total sediment discharge of coarse and fine particles simulated for a 7 mm deep flow over a cohesive soil surface when flow velocity ($u$) equalled either 10 mm s$^{-1}$ or 100 mm s$^{-1}$. 
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Figure 12. The relationship between the total, the fine and the coarse discharges and flow velocity for the simulations for a 7 mm deep flow over a cohesive soil surface.

Figure 13. Average value of $H_Z$ for 20 mm strips at various distances along the eroding surface observed at 5 minute intervals for the simulations for a 7 mm deep flow over a cohesive soil surface when flow velocity equalled 100 mm s$^{-1}$ and cohesion decreased $M_{p,d}$ in time according to Equation 10.

and the clearance rate and reduces the values of $H_R$ at any given point on the surface at any time. Often, cohesion increases with time of exposure to rain, particularly when soils develop surface crusts, and this results in a temporal reduction in $M_{p,d}$ for both coarse and fine particles for the $H_R=0$ condition. The effect of such temporal reductions in the $M_{p,d}$ values for $H_R=0$ on the values of $H_R$ is illustrated in Figure 13 through $H_Z$. The values of $M_{p,d}$ at any given time $T$ used in the associated simulation were calculated from

$$M_{p,d}(T) = M_{p,d} \exp(-0.322 \times T)$$  \hspace{1cm} (11)

where $T$ is the time since the start of the rain (minutes). Equation 11 results in the initial value of $M_{p,d}(T)$ being equal to $M_{p,d} \times M_{p,d}(5)$ equals 0.2$M_{p,d}$; $M_{p,d}(10)$ equals 0.04$M_{p,d}$; and $M_{p,d}(15)$ equals 0.008$M_{p,d}$. As can be seen from Figure 13, the average value of $H_R$ at the downstream end of the surface increased with time over the first 10 minutes and then fell. The discharge of fine sediment fell throughout the duration of the simulation (Figure 14). The discharge of coarse sediment initially increased before it became relatively constant for about 10 minutes. It then declined as the coarse particles detached much earlier were flushed from the bed.
Figure 14. Sediment discharges of coarse and fine particles simulated for a 7 mm deep flow over a cohesive soil surface when flow velocities equalled 100 mm s\(^{-1}\) and cohesion decreased \(M_{p,d}\) in time according to Equation 10.

Figure 15. Errors in the prediction of erodibilities for ridged plots from erodibilites determined on flat plots in the experiments reported by Elliot et al. (1989) using the interrill erosion model proposed by Kinnell (1993b) and currently used in WEPP and the WEPP slope gradient function.

Concluding Discussion

Raindrops impacting shallow flows detach soil material from the surface of the soil matrix and these detached particles move downstream in various ways depending on their size, density and shape, and the conditions existing in the flow. While the capacity of loose particles sitting on the surface to inhibit the detachment of soil particles from the surface of the soil matrix has been recognized for some time, it is difficult to set up laboratory and field experiments that enable interactions between the various modes of transport to be determined experimentally. However, mathematical simulations do provide an insight in such interactions. The simulations undertaken here were restricted to two particles sizes, one fine associated with RD-FT, the other coarse associated with RD-RIFT. Because of this, the model is directed at a very simple but somewhat unnatural situation. Even so, the results do provide some insight into the gross interaction between coarse and fine material and how that interaction may influence sediment discharge.

The results indicate that the flush of fine material that has been observed at the beginning of a rainstorm on a newly prepared cohesive surface and a subsequent increase in the discharge of more coarse sediment (e.g. Proffit et al., 1991) can be attributed to the build-up of coarse material on the bed. This result is to be expected given the existing theory on erosion by rain-impacted flow. However, the results presented here do illustrate how factors such a variations in
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flow velocity, particle settling velocity (which influences particle travel distance; Kinnell 2001) and cohesion may affect the build-up and decline of coarse material, and hence influence the discharge of fine and coarse sediment. It follows from this that the discharge of various sized sediments is highly dependent on local soil, rain and flow conditions and that extrapolating the results from one situation to another may produce unacceptable error. An example where such a situation occurred can be found in the results presented by Kinnell (1993b) in relation to soil erodibilities for the interrill erosion model later adopted in the Water Erosion Prediction Project, (WEPP) (Laflen et al., 1997). Figure 15 shows the level of error that occurred in relation to the prediction of soil erodibility for ridged surfaces from the soil erodibilities observed on flat surfaces using the slope adjustment factor adopted in WEPP

\[ S_f = 1.05 - 0.85 \exp(-4 \sin \phi) \]  

(12)

where \( \phi \) is slope angle. Less than half of the erodibilities determined for the ridged plots on 19 soils in the experiments reported by Elliot et al. (1989) could be predicted within 20 per cent from the erodibilities obtained on the flat plots.

References