THE EFFECT OF PRE-DETACHED PARTICLES ON EROSION BY SHALLOW RAIN-IMPACTED FLOWS

by

P.I.A. Kinnell

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Abstract

In shallow rain-impacted flows, particles detached from the soil matrix will produce a layer of pre-detached particles on an eroding surface when entrainment by flow is absent. This layer provides a degree of protection to the underlying soil matrix and material from the layer also contributes to the discharge of sediment across the downstream boundary of an eroding area. The development and effects of the layer are dynamic. The layer tends to be more protective at low flow velocities and with coarse particles than at high velocities and with fine particles. The ease by which particles can be detached from the soil matrix also influences the development of the layer. The dynamic nature of the layer results in the susceptibility of a surface to erosion by rain-impacted flow varying in time and space. The consequence of this is examined with respect to erodibilities associated with an erosivity index that is based on the product of runoff rate from a 40 m long plot and the expenditure of rainfall kinetic energy.

Introduction

Shallow rain-impacted flows often during rainfall erosion. They are also common in sheet and inter-rill erosion areas. Inter-rill erosion may influence rill morphology and may contribute to the movement of nutrients and pollutants over the landscape.(eg.Proffitt and Rose, 1991)

Kinnell (1990,1991) developed a theory for erosion by rain-impacted flow. The theory is based on the observation that once disturbed by a drop impact, most particles travel limited distances from the point of drop impact. For flows deeper than 4 mm, Kinnell (1991) showed that increases in flow depth reduces the rate at which sediment was transported by flows bombarded by medium (e.g., 2.7mm diameter) to large (e.g., 5.1mm diameter). Sediment transport was also shown to vary directly with flow velocity and rainfall intensity.

Although the erosive stress applied through the flow to the underlying surface has a major influence on erosion, the reaction of that surface is also important. On soil surfaces, particles detached upstream form a layer of pre-detached particles above the soil matrix in the downstream areas of surfaces eroded by rain-impacted flows (Hairsine 1988, Borah 1989, Kinnell 1990, Hairsine and Rose 1991, Proffitt et al 1991). In this paper, the results of computer simulations and field experiments are used to illustrate the effect of this layer on sediment discharge from soil surfaces being eroded by rain-impacted flow. Also,data from field experiments are discussed in relation to the effect of pre-detached material on soil erodibilities observed during natural rainfall events.

Theory

When unimpacted flow occurs, or flows are deep enough to prevent raindrops from detaching soil material underlying the flow, sediment discharge varies with the shear stress (τ) of the flow when the shear stress exceeds a critical value (Foster, 1982). This critical value, which is depicted as $\tau_{c.M}$ in Fig. 1 is highly influenced by cohesion and interparticle friction in the soil surface. Rilling can only occur when $\tau > \tau_{c.M}$.

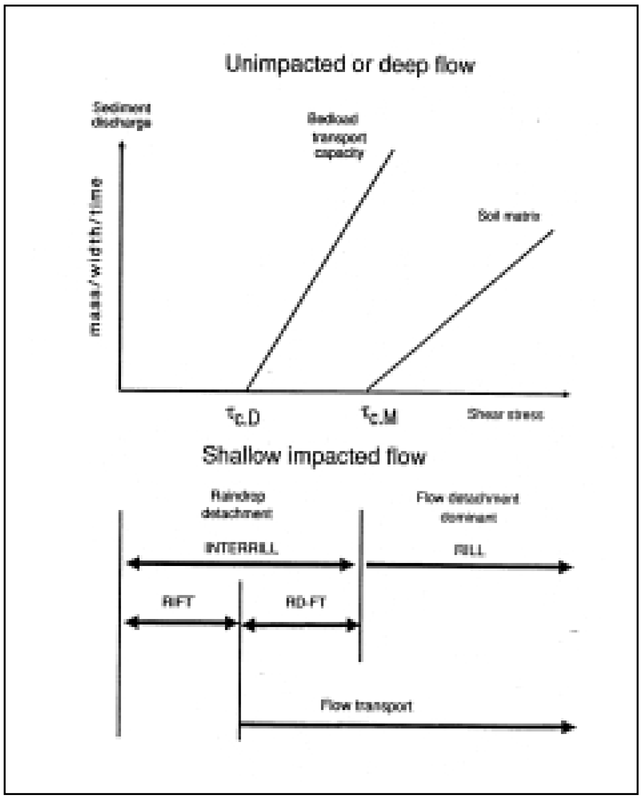

Fig. 1. Schematic diagram of sediment discharge – shear streaa relationships for unimpacted deep flow and rill – interill relationships in shallow rain - impacted flow

Because they are not held within the soil matrix by cohesion and interparticle friction,loose particles sitting free on the soil surface may be entrained when the shear stress is less than $\tau_{c.M}$. Suspended load material is transported whenever $\tau>0$ but a critical shear stress has to be exceeded for bedload transport. This critical shear stress, depicted by $\tau_{c.D}$ in Fig. 1, is less than $\tau_{c.M}$. As a consequence, particles detached from the soil matrix by sheet or interrill erosion processes and not transported by suspended load can be transported by the flow up to a maximum ratedetermined by the bedload transport capacity when $\tau > \tau_{c.D}$. The characters RD-FT (for raindrop detachment + flow transport) are used to indicate when this condition occurs in Fig. 1. When $\tau < \tau_{c.D}$, the combined action of raindrop impact and flow is necessary for the transport of material detached by drop impact. The transport process that operates as a consequence of this interaction between raindrop impact and the flow has been called raindrop-induced flow transport (RIFT) (Kinnell, 1988).

When raindrops impact shallow flows that would otherwise not entrain soil material, any particle disturbed by a drop impact travels downstream a distance (x_p) that varies with the time the particle remains suspended (t_p) and the mean flow velocity (u):

$$x_p = t_p\, u \qquad (1).$$

t_p varies with directly with the height (z) to which particles are lifted and inversely with the settling velocities (v_p) of the particles. For particles with a given characteristic (e.g., size (p)), the average distance travelled (x'_{pd}) following the impact of a drop of size d varies from 0 for immobile particles (e.g., gravel, large aggregates) to a value close to infinity for suspended load. x'_{pd} is also large for any particle that is entrained by the flow when it falls back to the soil surface after being detached from the soil matrix by a drop impact – ie for RD-FT.

x'_{pd} determines the extent of an active zone that is associated with particles having a given characteristic (Kinnell 1990, 1991). Drop impacts in this active zone cause particles to pass immediately across its downstream boundary. Drops impacting upstream of this zone do not. Thus, for any arbitrary boundary orthoginal to the direction of flow, the rate (q_{sR}) at which sediment with a given particle characteristic is discharged across a unit width of the boundary is given by

$$q_{sR}(p,d) = F_d\, x'_{pd}\, D_{pd} \qquad (2)$$

where F_d is the spatially averaged frequency of drops of size d and D_{pd} is the average mass of the particles lifted into the flow by each drop impacting in the active zone associated with particles of size p. For particles not travelling as suspended load, combining Eqs. 1 and 2 gives

$$q_{sR}(p,d) = F_d\, t'_{pd}\, u\, D_{pd} \qquad (3)$$

where t'_{pd} is the average time particles of size p remain suspended in the flow following the impact of a drop of size d. Since a number of drop sizes occur in natural rainfall, and a number of particle sizes and particle densities exist in the sediment discharged from most soils, usually a number of active zones operate simultaneously. Intergration of Eq.3 with respect to particle and rain characteristics provides a means of calculating the sediment transport rate ($q_{sR}(s,r)$) associated with a soil s and a rain r.

When drops impact shallow flows over soil surfaces, they may lift both particles from the soil matrix and loose pre-detached soil particles sitting on the soil surface. If present, the pre-detached particles are lifted into the flow first and particles are detached from the soil matrix only if sufficient energy remains after this has happened. The pre-detached particles thus provide a degree of protection to the soil matrix below them. The protection provided can be considered through H, a parameter that varies from 1 when the soil matrix is fully protected to 0 when no pre-detached are present on the soil surface (Hairsine 1988, Hairsine and Rose 1991). Consequently,

$$D_{pd} = H_{Rlpd}.D_{pd.D} + (1-H_{Rlpd})D_{pd.M} \qquad (4)$$

where H_{Rlpd} is the local value of H associated with the impact of a drop of size d and a particle of size p[#], $D_{pd.D}$ is the value of D_{pd} obtained when pre-detached particles completely protect the soil matrix and $D_{pd.M}$ is the value of D_{pd} obtained when no pre-detached particles are present on the soil surface. $D_{pd.D}$ is determined by factors such as particle size, shape and density which influence the mobility of the pre-detached particles. $D_{pd.M}$ is determined largely by interparticle friction and cohesion. It follows mathematically from Eq.4 that if the D_{pd}:$D_{pd.D}$ and $D_{pd.M}$:$D_{pd.D}$ ratios are known, H_{Rlpd} can be calculated from

$$H_{Rlpd} = \frac{D_{pd}\, D_{pd.D}^{-1} - D_{pd.M}\, D_{pd.D}^{-1}}{1 - D_{pd.M}\, D_{pd.D}^{-1}} \qquad (5)$$

when $1 > D_{pd.M}\, D_{pd.D}^{-1}$.

In very shallow flows, increases in flow depth produce a positive effect on the rate sediment is transported by rain-impacted flow (Rauws and Govers, 1988) but the effect is reversed for deeper flows (Mutchler and McGregor 1983). These effects can be accounted for through the use of the equation

$$D_{pd}t_{pd} = k_p\, f'(h,d) \qquad (6)$$

where kp is a coefficient that depends on the susceptibility of p sized particles to erosion by rain-impacted flow and f'[h,d] is a function that accounts for the interaction between flow depth (h) and the impacting raindrop of size d (Kinnell and Wood, 1992). Combining Eqs. 4 and 6 gives

$$D_{pd}t'_{pd} = [H_{Rlpd}.k_{p.D} + (1-H_{Rlpd})k_{p.M}]\, f'(h,d) \qquad (7).$$

where $k_{p.D}$ and $k_{p.M}$ are the respective susceptibilities of the deposited and soil matrix particles to erosion by rain-impacted flow. The square bracketed term accounts for interactions between the impacting raindrops and the surface underlying the flow and thus includes the effect of what is commonly termed the erodibility of the eroding surface. Combining Eqs. 3 and 7 gives

$$q_{sR}(p,d) = F_d\, u\, [H_{Rapd}\, k_{p.D} + (1 - H_{Rapd})k_{p.M}]\, f'\{h,d\} \qquad (8)$$

where H_{Rapd} integrates the spatial variation in H_{Rlpd} over the active zone associated with p and d.

F_d increases with the intensity of rain of a given drop size and decreases with d^3. Thus it follows that, for rain r,

$$q_{sR}(p,r) = I\, u\, [H_{Rapd}\, k_{p.D} + (1 - H_{Rapd})k_{p.M}]\, f^*\{h,r\} \qquad (9)$$

where I is the rainfall intensity, and, given Nd different drop sizes in a rainfall,

$$f^*\{h,r\} = \sum_{i=1}^{Nd} (f^*\{h,d\}P_d)_i \qquad (10)$$

[#] **Pre-detached particles also have an influence on detachment by flow (FD). H_R is used here in relation to the protective effect of pre-detached particles on raindrop detachment (RD) because the coefficient of protection that applies to flow detachment (which, for example could be termed H_F) may differ from H_R.**

where P_d is the proportion of the rain contributed by each drop size, and

$$f^*\{h,d\} = f'\{h,d\}/\pi d^3 \qquad (11).$$

From Kinnell (1993),

$$f^*\{h,d\} = 0.001h \exp(-0.207h) \qquad ,h<h_c \qquad (12a)$$

$$f^*\{h,d\} = 0.001h \exp(-0.207h_c - b_d(h - h_c)) \qquad ,h\leq hc \qquad (12b)$$

where

$$h_c = 1.017 + 4.111 \log(d) \qquad (13)$$

and

$$b_d = \exp(0.585 - 0.387d) \qquad (14)$$

when h and d are expressed in millimetres and $f^*\{h,d\}$ in metres . The convergence of $f^*\{h,d\}$ to a common relationship for all drop sizes when flows are very shallow results, as noted earlier, from the water surface restricting the height to which particles are lifted in these very shallow flows (Kinnell, 1993).

For soil s under rain r, integration of Eq. 9 over the range of particle sizes present in the eroding materials results in

$$q_{sR}(s,r) = I\,u\,[H_{Rg}\,k_{s.D} + (1 - H_{Rg})k_{s.M}]\,f^*\{h,r\} \qquad (15)$$

where H_{Rg}, the global value of H_R, integrates the spatial variation in H_{Rlpd} over all the active zones associated with the soil s and the rain r, and $k_{s.D}$ and $k_{s.M}$ are the respective susceptibilities of the deposited and soil matrix materials to erosion by rain-impacted flow. $k_{s.D}$, and $k_{s.M}$ have units of $kg.s/m^4$ when q_{sR} is in kg/m.s, u is in m/s, I is in m/s, and $f^*\{h,r\}$ is in m.

In the context of the theory related to Eq. 15, three parameters ($k_{s.D}$, $k_{s.M}$ and H_{Rg}) influence the erodibility of the soil surface when erosion results from rain-impacted flow. It has been proposed (Proffitt et al 1989) that H_{Rg} takes on a standard value of about 0.9 when dynamic equilibrium conditions exist on soil surfaces. However, H_{Rlpd} is an extremely dynamic factor. H_{Rlpd} is highly dependent on x'_{pd}. If x'_{pd} is 0, as would be the case if the particles were completely immobile, then $H_{Rlpd} = 1$ over the entire surface when dynamic equilibrium conditions occur. Conversely, if x'_{pd} is greater than the length of the eroding surface, as would be the case if the particles detached by the drop impacts were all subsequently entrained by the flow as soon as the fall back to the soil surface, $H_{Rlpd} = 0$ over the entire surface when dynamic equilibrium conditions occur. Since x'_{pd} is dependent on both flow velocity and particle characteristics, H_{Rg} at dynamic equilibrium will vary between soils and with flow velocity. The effects on H_{Rlpd} of factors such as x'_{pd} and the ratio of $D_{pd.M}$ to $D_{pd.D}$ can be illustrated through computer simulation of the processes of detachment, uplift and downstream movement of detached particles associated with individual drop impacts.

COMPUTER SIMULATION OF THE RAINDROP IMPACT INDUCED SEDIMENT TRANSPORT PROCESS

The computer model

The transport process induced by raindrops impacting shallow flows has been termed raindrop-induced flow transport (RIFT) (Kinnell 1988). Fig.2A shows schematically the processes of detachment, uplift and downstream movement of detached particles associated with individual drop impacts. For simplicity, downstream movement during uplift is omitted from this figure. Fig.2B shows schematically the manner in which these processes are considered in the computer model.

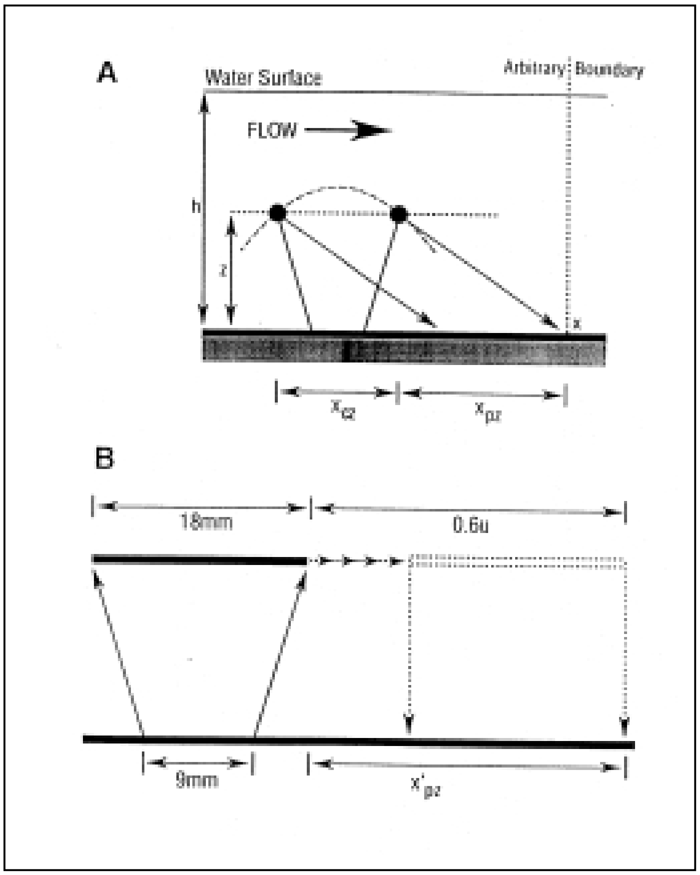

Fig. 2. Schematic representation of particle uplift, downstream travel and fall in (A) rain-impacted flow (after Kinnell (1990) and (b) the computer model.

The computer model is based on the scheme shown in Fig.2A but some modifications have been made in order to provide a relatively simple model. Firstly, in the model, the area of the bed disturbed by a drop impact is assumed to be square rather than circular in shape. Secondly, in Fig.2A, the cloud is depicted as being hemispherical. In the model, the cloud is considered to be flat and square with 18mm sides (Fig. 2B). Visual observation of the clouds that occurred during the experiments reported by Kinnell (1991) indicate that the maximum cloud widths for 5.1mm drops impacting flows about 5mm deep were about 20mm. Relatively flat clouds result from the water surface restricting the height particles can be lifted by the impact of large raindrops within shallow flows. Thirdly, in the model, it is assumed that the integrated effect of z on x_p can be represented by a single z and hence, only the effective average travel distance (x'_{pd}) need be considered for each drop impact.

In the model, the particles are assumed to remain suspended for 0.6s so that x'_{pd}=0.6u (Fig. 2B). This is consistent with the observations reported by Kinnell (1990) for 5.1mm drops impacting 5mm deep flows over 0.2mm sand. The area disturbed by a drop impact is assumed to be 9mm x 9mm. This is also consistent with observations of 5.1mm drops impacting 5mm deep flows. Each drop impact is assumed have the capacity to lift up to 100 particles per square millimetre when H_{Rlpd} =1. This assumption is arbitrary.

. Flow depths and velocities are assumed not to vary in time and space. Under these circumstances, sediment transport can only be simulated for conditions where the inflow of water from the rain is insignificant compared with the inflow from upstream or where the rainfall and infiltration rates are comparable.

In the program, the target area is considered to be made up of 1mm by 1mm square elements and the computer's inbuilt random number generator is used to determine the position of the drop impact within the 100m by 240mm area. Insufficient memory space is available in many MS-DOS based PC systems to simulate RIFT on the 500mm by 500mm area used in the experiments reported by Kinnell (1990,1991). However, material passing over a side boundary as a result of impacts close to the edge is deposited in the relevant area on the other side of the target. Thus the target is effectively a window in a much wider area. Flow depths and velocity are assumed not to vary in time and space. Under these circumstances, sediment transport can only be simulated where the inflow of water from rain is insignificant compared with the inflow from upstream or where rainfall and infiltration rates are comparable. The simulation could be considered relevant to, for example a 240mm segment of rain-impacted flow that occurs immediately downstream of a segment of flow that has been fully protected from vegetation by short vegetation.

As noted earlier, $D_{pd.D}$ is associated with 100 pre-detached particles per square millimetre of the bed. In order to examine the effect of varying cohesion, the computer model enables the user to select the $D_{pd.M}$:$D_{pd.D}$ ratio. For impacts on surfaces with pre-detached material, the model calculates the capacity of the cloud that remains after the pre-detached material is lifted into the cloud and then uses this capacity and the user-selected $D_{pd.M}$:$D_{pd.D}$ ratio to calculate the amount of material that is lifted into the cloud from the soil matrix. Once this process is completed, the cloud is moved a distance x'_{pd} from the position of the drop impact and the material in the cloud added to the respective 1mm^2 elements on the surface below. The model thus maintains a record of the detached material contained in each 1mm^2 element on the target between each drop impact.

The influence of x'_{pd} and the $D_{pd.D}$:$D_{pd.M}$ ratio on H_{Rlpd}

Fig. 3 shows the local values of H_R (H_{Rlpd}) calculated using Eq. 5 in conjunction with the values of $D_{pd}.D_{pd.D}^{-1}$ produced by the model for 2000 drop impacts after 72000 drop impacts when various flow velocities and ratios of $D_{pd.M}$ to $D_{pd.D}$ are used. Flow velocity affects x'_{pd}, the effective average distance a particle of size p travels after being lifted from the bed by a drop of size d, and x'_{pd} has a major influence on the value of H_{Rlpd} produced when dynamic equilibrium conditions are reached. If, for example, there is no flow so that x'_{pd} = 0, then, as noted earlier, H_{Rlpd} must be equal to 1 over the whole surface at dynamic equilibrium if there is no other mechanism to transport the particles lifted from the surface. If, on the other hand, the flow velocity exceeds the critical velocity needed to entrain a loose particle of a particular size, x'_{pd} for particles of that size lifted into the flow by a drop impact is greater than the distance to the end of the eroding surface. If these particles are the least transportable of the particles yielded to the flow by the drop impact, then

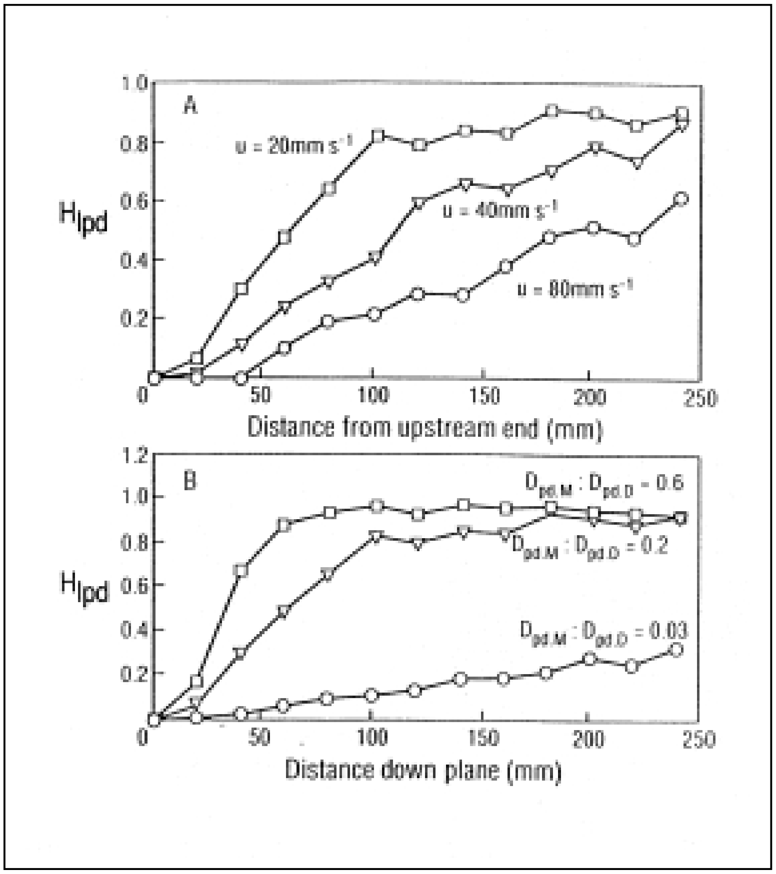

Fig. 3. The effect of (A) flow velocity and (B) $D_{pd.M}$ to $D_{pd.D}$ ratio on H_{RIpd} produced after 72,000 simulated drop impacts on a 100mm by 240mm cohesive surface using random drop impacts

H_{RIpd} must be zero over the whole surface at dynamic equilibrium. If these particles are not the least transportable one, then H_{RIpd} lies between 0 and 1. Since x'_{pd} is influenced by both particle characteristics and flow velocity, H_{RIpd} at dynamic equilibrium will vary between soils and, as illustrated in Fig.3A, decrease with flow velocity when entrainment by flow is absent. Also, since x'_{pd} is influenced by particle characteristics, the local values for H_R for a soil (H_{RIs}) will vary between soils as well as with flow velocity.

Fig.3B shows that H_{RIpd} increases with the ratio of $D_{pd.M}$ to $D_{pd.D}$. Variations in H_{RIpd} are determined, on one hand, by the rate of detachment of particles from the soil matrix and, on the other hand, the rate detached particles are transported from their initial point of detachment. Both x'_{pd} and the ratio of $D_{pd.M}$ to $D_{pd.D}$ influence the relativity between the rate of detachment of soil particles from the soil matrix and rate of the subsequent downstream transport of these detached particles. Consequently, increases in cohesion in the soil matrix tend to produce decreases in H_{RIs}.

FUNDAMENTALS OF A NUMERICAL MODEL OF EROSION BY RAIN-IMPACTED FLOW

The results of computer simulation of the detachment and transport processes associated with RIFT described above illustrate the effect of a dynamic layer pre-detached particles on erosion by shallow rain-impacted flow. This layer, which, because of its nature, will hereafter be referred to as the Dynamic Depositional Layer (DDL), tends to increase in effect as time and distance increase whenever entrainment by overland flow is absent. It also acts as a source of easily eroded material when entrainment commences. However, developing a more sophisticated simulation of the detachment, uplift and depositional events for individual drop impacts would produce a model that would be computationally too intensive for use on large areas. Other techniques are more appropriate for large areas.

Numerical models of surface-water flows often use finite difference techniques. Such models can be provide a framework for modelling RIFT numerically. Given certain assumptions, mass balance techniques can be used to determine the sediment transported through and deposited within an element. Linking the elements provides a model that can be applied at various scales.

Fundamentals relating to the determination of H_{Rlpd}

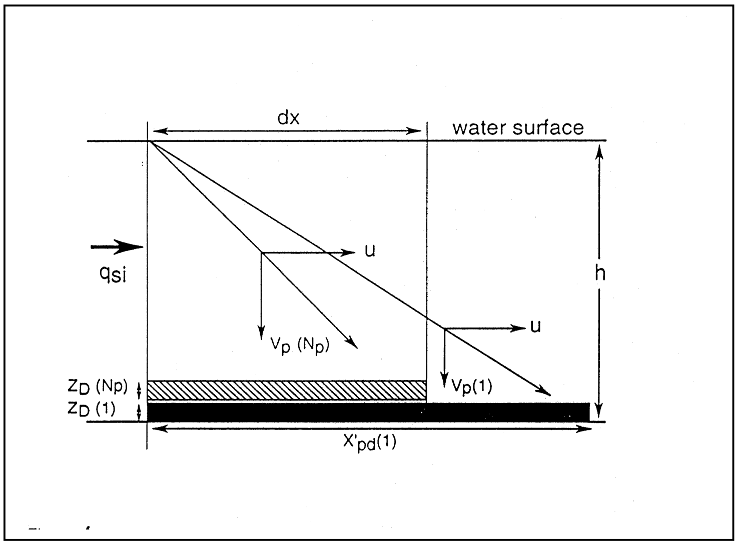

Fig. 4. Schematic diagram of travel during the deposition of the smallest (1) and the largest (Np) non-suspended load particles entering an element of flow

Given a mass (q_{sip}) of p sized particles entering an element in unit time, Fig. 4 shows how detached particles are deposited on the surface underlying the flow when it is assumed that the particles entering the flow are of uniform size and are distributed uniformly through the depth of the flow. Given an element of unit width, the mass of particles is deposited over an area x'_{pd}. Thus, the depth of the deposit (z_{Dp}) is given by

$$z_{Dp} = \frac{q_{sip}}{\rho_D \, x'_{pd}} \qquad (16).$$

where ρ_D is the bulk density of the deposit. If q_{smp} is the mass of p sized particles leaving an element in unit time when $H_{Rlp}=1$ (the local value of H_R for particles of size p), then the depth of the deposit when $H_{Rlp}=1$ is given by

$$z_{Dp} = \frac{q_{smp}}{\rho_D \, x'_{pd}} \qquad (17).$$

If H_{Rlp} varies linearly with the depth of the deposit when $H_{Rlp}<1$ then, from Eqs. 16 and 17,

$$H_{Rlp} = \frac{q_{sip}}{q_{smp}} \quad , q_{sip} \leq q_{smp} \qquad (18a)$$

$$H_{Rlp} = 1 \quad , q_{sip} > q_{smp} \qquad (18b).$$

Eq. 18 is valid when $\delta x \leq x'_{pd}$. Although, as can be seen from Fig. 4, not all the material entering an element is deposited within that element when $\delta x \leq x'_{pd}$, the assumption that the detached particles are uniformly distributed throughout the depth of flow when the particles enter the element results in the particles being uniformly deposited over the soil surface. Consequently, partitioning q_{sip} into material passing through and material being deposited in an element is not required in the calculation of the depth of material deposited in the element.

Eq. 9 provides a means of calculating values of q_{smp} and q_{sip}. when H_{Rapd}, $k_{p.D}$, $k_{p.M}$ and the drop size characteristics of the rain are known. Also, using a value of $H_{Rapd} = 1$ in Eq. 9 enables the value of q_{smp} to be estimated when the particle size characteristics of the detached particles are known. Thus, given a starting value of H_{Rapd}, Eqs. 9 – 18 provide a mechanism for numerically modelling the development of the DDL in time and space when they are used in conjunction with a numerical model of surface water flow.

Modelling the sorting of sediment by RIFT

Most natural eroding surfaces contain a number (N_p) of different sized particles with the result that usually there are a number of values of x'_{pd} associated with material entering any element. If the deposition process occurs without interference from raindrop impact, then it follows from Fig. 4 that sorting of the detached particles occurs so that the material in the DDL at points closer to the upstream boundary of an **element** will tend to be coarser than the material in the DDL at points further downstream. Consequently, the particle size distribution of the material in the DDL varies temporally and spatially and it is necessary in any numerical model of RIFT to estimate both that mass of the material deposited within an element and the mass passing straight through. This can be achieved when particles entering an element are uniformly distributed through a known depth of flow. This is probably the case when the water surface restricts the height to which particles are lifted but difficulties arise when modelling RIFT with deeper flows where the height to which particles are lifted is unknown.

Table 1 shows the result of applying the principles outlined above in a numerical model of RIFT designed to determine the possible steady-state composition of DDL produced by natural rain at 50 mm/hr on a 3 m long impervious sandy soil surface when cohesion restricted $k_{p.M}$ to $0.01k_{p.D}$. The composition of the original material was assumed to be the same as that for the sand used by Walker et al (1978), and the spatial variation in flow depth was assumed to be given by

$$\log (h) = -1.162 + 0.431 \log (q_w) \qquad (19).$$

when h is in mm and q_w is the flow discharge in ml/m/s. This relationship results from the flow depths measured by Walker et al for rain-impacted flows on their sandy surface when it was inclined at 5%. The drop-size distribution for the rain was assumed to be that measured by Hudson (1963). As is to be expected, Table 1 shows H_{Rls} to increase and the DLL to become coarser in the downstream stream direction.

Table.1. Proportion of particles in original soil and in the DDL, and values of f*{h,r}, H_{Rls} and q_{so} (sediment discharge) at various points along a 3 m plane produced by the numerical model for steady-state conditions with 50mm/h rainfall, $k_{p.M} = 0.01k_{p.D}$, a slope gradient of 5%, and the drop-size distribution for natural rain as determined by Hudson (1963).

Particle Size (mm)	Original Soil	DDL 0.042 m	DDL 0.222 m	DDL 0.942 m	DDL 2.142 m	DDL 3.0 m
	proportion of particles					
0.0014	0.006600	0.000000	0.000000	0.000000	0.000000	0.000000
0.0033	0.002300	0.000001	0.000000	0.000000	0.000000	0.000000
0.0058	0.006600	0.000010	0.000008	0.000005	0.000005	0.000005
0.0117	0.009600	0.000109	0.000083	0.000057	0.000052	0.000048
0.0234	0.011200	0.000932	0.000706	0.000488	0.000441	0.000412
0.0471	0.036700	0.011734	0.011737	0.010525	0.010047	0.009514
0.0755	0.063300	0.029159	0.029166	0.029209	0.029225	0.029242
0.0965	0.035700	0.019911	0.019916	0.019946	0.019957	0.019968
0.1150	0.078000	0.049682	0.049695	0.049768	0.049795	0.049823
0.1370	0.081000	0.058382	0.058397	0.058483	0.058515	0.058548
0.1630	0.063000	0.050806	0.050819	0.050894	0.050921	0.050950
0.1935	0.058000	0.051690	0.051704	0.051780	0.051808	0.051837
0.2300	0.068000	0.066300	0.066317	0.066415	0.066451	0.066489
0.2735	0.062000	0.065497	0.065514	0.065611	0.065646	0.065684
0.3585	0.094000	0.110351	0.110379	0.110542	0.110601	0.110665
0.4600	0.076000	0.097530	0.097555	0.097699	0.097751	0.097807
0.5425	0.043000	0.058106	0.058121	0.058207	0.058238	0.058271
0.6460	0.051000	0.072494	0.072513	0.072620	0.072659	0.072701
0.7740	0.044000	0.065738	0.065755	0.065852	0.065887	0.065925
0.9205	0.032000	0.050029	0.050042	0.050116	0.050143	0.050171
1.3400	0.047000	0.080308	0.080329	0.080447	0.080491	0.080537
1.8400	0.015000	0.027736	0.027743	0.027784	0.027799	0.027815
3.0000	0.013000	0.026703	0.026710	0.026749	0.026764	0.026779
4.5000	0.003000	0.006789	0.006791	0.006801	0.006805	0.006809

	0.042 m	0.222 m	0.942 m	2.142 m	3.0 m
h (mm)	0.25	0.51	0.95	1.35	1.56
f*{h,r} (m)	2.31e-4	4.46e-4	7.56e-4	9.75e-4	1.07e-3
H_{Rls}	0.1787	0.2282	0.3167	0.3442	0.3664
q_{so} (kg/m/s)	3.56e-6	2.22e-5	1.14e-4	2.53e-4	3.56e-4

THE EFFECT OF THE DDL ON ERODIBILITIES ASSOCIATED WITH EMPIRICAL EROSION MODELS

Kinnell (1993) proposed that the product of runoff rate (Q) and the rate of expenditure of rainfall kinetic energy (E_A) could be used as the basis of an index of the erosive power of rainfall when sheet erosion was the dominant form of erosion. It follows from Eq. 18 of Kinnell (1993) that, given a rainfall event of duration T, the soil lost per unit area (A_e) from a bare eroding surface is given by

$$A_e = K_e\, L_f\, S_f \sum_{j=1}^{T} (Q\, E_A)_j \qquad (21)$$

where Ke is the average susceptibility of the eroding surface to erosion during the rainfall event, Lf is a factor dependent on slope length, Sf is a factor dependent on slope gradient, Q is the runoff during time interval j and E_A is the amount of rainfall energy expended per unit area during that time interval. Eq. 18 of Kinnell is based on the observation that q_w is the product of h and u and is also related to runoff rate (ie. Q), flow depth varies with slope length and gradient, and both f*(h,d)/h and the kinetic energy per unit quantity of rain are influenced by raindrop size and velocity.

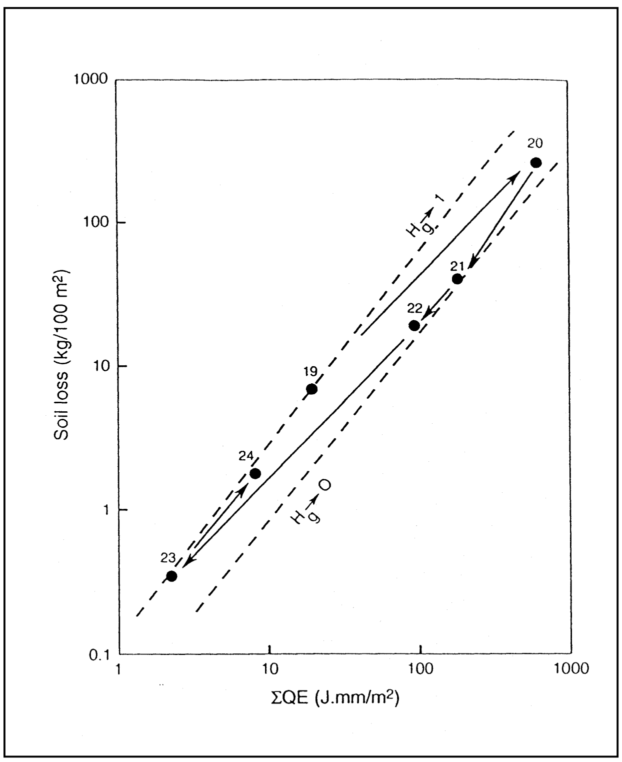

Fig 5. The relationship between storm soil loss from a 40 m long 2.6 m wide non-vegetated plot on a 4.2 % slope and the QE_A index (sum of the product of runoff rate and the rate of expenditure of rainfall kinetic energy during an erosion event) for a number of rainfall events in the experiments by Kinnell (1983, 1985)

Fig. 5 shows the relationship between the QE_A index (the sum of the product of Q and E_A over the duration of an erosion event) and soil loss for the event from a 40 m long, 2.6 m wide non-vegetated runoff and soil loss plot with a slope gradient of 4.2 % in the experiments reported by Kinnell (1983, 1985). The soil used in these experiments was an Albaqualf (Singer and Walker, 1983) that rapidly formed a surface seal and crust during rain following cultivation. This crusted surface was highly resistant to rilling so that sheet erosion was the dominant erosion process that occurred on the plot most of the time. 18 rainfall events (assuming that rainfall events are seperated by periods of 30 mins or more with no rain) occurred between the time the plot was cultivated and the series of event shown in Fig. 5.

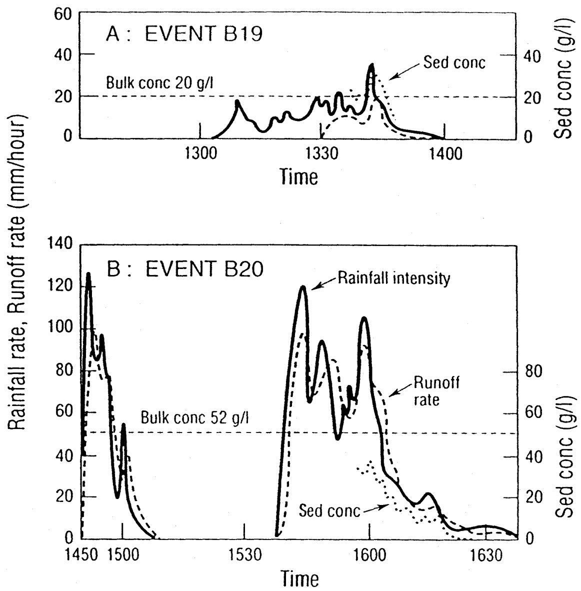

Fig. 6. Rainfall, runoff and sediment concentrations measured from the non-vegetated plot durimg events 19 and 20 in Fig. 5.

Most empirical models of rainfall erosion (eg, the Universal Soil Loss Equation) assume that the susceptibility of the soil to erosion does not vary significantly within and between erosion events. However, the need to consider the effect of the DDL under field conditions is illustrated by the data shown in Fig.6. The two events occurred on the same day. During event 19, a considerable amount of pre-detached material lay on the surface as a result of raindrop impact prior to and during the event and the peak in the erosive stress that occurred towards the end of the event resulted in above average sediment concentration. However, during event 20, the flow conditions were such that, at some point x on the eroding surface (Fig. 7), $\tau>\tau_{c.D}$ (Fig.1) so that pre-detached material was

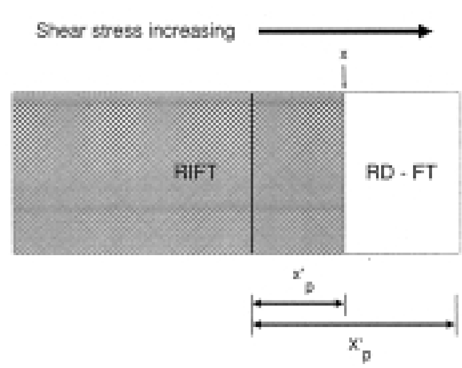

Fig. 7. Schematic diagram of the effect of entrainment of detached particles beginning at a point x on an inclined surface. RIFT refers to raindrop induced flow transport (both raindrop impact and flow involved in transport phase). RD-FT refers to raindrop detachment and flow transport. X'_p indicates the extent of the zone where material detached by raindrop impact passes across the boundary without further aid from raindrop impact

flushed from the downstream end of the eroding surface but there was no rilling. Consequently, during the latter part of this event, the susceptibility of the soil to erosionwas dominated by $k_{s.M}$, and the period of high erosive stress towards the end of the event produced lower than average sediment concentrations. During event 19, the susceptibility of the soil to erosion was dominated by $k_{s.D}$. Thus, the value of K_e for event 20 was less than the value of K_e for event 19. Events 21 and 22 occurred a week later but produced reasonably high runoff rates soon after they began. These runoff rates were sufficient to keep the surface relatively free from pre-detached particles. Event 23 occurred a week after event 22 and was similar to event 19. Runoff did not occur during the first half hour of then event and, when it did, runoff rates were low. These conditions led to the re-establishment of the DDL over the whole of the plot and it persisted during event 24. These between and within storm variations in erodibility result in the response to variations in the erosive power of rainstorms lying within limits such as those indicated by the dotted lines in Fig. 5.

SUMMARY AND CONCLUSION

Three models of erosion by rain-impacted flow have been considered in this paper. The first uses Eqs. 3-5 in a simulation of the detachment and deposition processes associated with individual drop impacts. This model was used to demonstrate spatial variation in the protective effect of the dynamic depositional layer (DDL) on the soil matrix and the influence of flow velocityand cohesion on the protection provided by the DDL. The second model used Eqs. 9-18 to provide a mecahnism for numerically modelling the development of the DDL in time and space using a finite difference approach. The model was used to demonstrate the coarsening of the DDL in the downstream direction. Rather than using Eqs. 9-18, the model could have been based on the theory of Hairsine and Rose (1991). However, in the Hairsine and Rose theory, deposition is considered to be a one dimensional process whose rate depends on sediment concentration, and the development of the DDL depends on the balance between detachment and the deposition processes. In the theory used here, deposition is considered to be a two dimensional process that does not rely on the determination of sediment concentration. Also, the need to determine the balance between detachment and deposition means that modelling non-steady conditions via the Hairsine and Rose theory requires connsideration of quasi steady states. Although Eqs. 9-18 were applied to a steady-state situation in this paper, they can be readily applied to non-steady conditions.

Practical models of rainfall erosion can be developed from simplification of relative complex ones. The third model considered here results from the observation that (a) flow discharge is given by the product of flow depth (h) and flow velocity(u) and is also related to the runoff rate (Q), (b) flow depth varies with slope length and gradient and (c) both f*(h.d)/h and the kinetic energy per unit quantity of rain are influenced by raindrop size and velocity. The QE_A index that results from these observations has the potentialto provide a ore direct consideration of hydrology in the Universal Soil Loss Equation environment. The I_XE_A index, uses the excess rainfall rate (I_X) as a surrogate for Q, has bee shown to apply to sheet erosion (Kinnell, 1983) and outperform the EI_{30} index when rilling occurs (Armstrong, 1990). Models such as the USLE do not consider that major variations in the susceptibility to erosion occur between and within rainfall events. However, consideration of the characteristics of a number of natural rainfall-runoff events in relation to the understandings of the behaviour of the DDL outlined in this paper indicate that more accurate predictions of soil loss could result if the effect of the DDL on the susceptibility of the soil surface to erosion is taken into account.

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