

CHAPTER 1

INTRODUCTION

Raindrops impacting shallow surface-water flows can lift particles from the underlying surface (bed) into the flow. While in the flow, these particles are subjected to horizontal forces related to the motion of the fluid and, as a result, they move downstream as they rise and fall back to the bed. Depending on the conditions of the flow, and the size and density of the particles, some of the particles that return to the bed remain there until they are once again disturbed by a drop impact. The downstream movement of these particles relies on the combined action of raindrop impact and the downstream movement of the surface-water. Because the flow cannot transport these soil particles without the stimulus from raindrop impact, the process has been called raindrop-induced flow transport (RIFT, Kinnell, 1988). The research reported here centres on this process.

1.1 THE ROLE OF RIFT IN RAINFALL EROSION

Consider when rain begins to fall on a bare soil surface and no surface water is present. The impacting raindrops are often capable of detaching soil material from the soil matrix but splash is the only mechanism that operates to transport this detached material at this stage. On level surfaces, splash moves material radially away from the point of impact. While a considerable amount of detached soil material may be moving aerially in the splash, no erosion occurs unless some factor causes splash to travel further in one direction than another. Sloping surfaces promote the net downslope movement of splash, the transport rate across any arbitrary boundary orthogonal to the direction of slope increasing with slope gradient (Ekern, 1950). However, wind may overcome the net directional movements imposed by slope gradient so that downslope movement of detached material by drop splash may not be always certain.

As time progresses and the rainfall rate exceeds the infiltration rate, a layer of water develops on the surface. This surface water flows downslope and accumulates in any depressions that occur in the surface. The development

of very thin films of surface water enhances the ability of raindrops to detach and transport soil material by splash (Park et al., 1982). However, as the depth of the water increases towards a few millimetres, this effect is reversed. Consequently, there tends to be a net movement of soil material by splash from those areas covered by little or no surface water to the depressions containing the deeper water (Moss, 1988). Thin surface-water flows occur between the higher points on the surface and the depressions. In all flows, some of the detached soil material may be transported as suspended load, so that even unimpacted thin surface-water flows may transport material to the depressions. Unimpacted thin flows, because of their low shear velocities, are usually incapable of transporting anything but suspended load. However, since RIFT occurs when shallow flows are impacted by erosive raindrops, RIFT may contribute to the movement of the coarser soil material to the depressions at this stage. Some experiments (e.g., Bradford et al., 1987) indicate that the amount of material transported to the depressions by rain-impacted flows shallower than a few millimetres may be similar to that transported by drop splash.

As time progresses and/or the rainfall rate increases, water starts to flow between the major depressions in the landscape. This marks the onset of runoff. Prior to runoff commencing, sediment moves essentially from the high points to the depressions. Little soil material is lost across the downslope boundary of any large area of soil. If this situation continued indefinitely, all the depressions would eventually become filled with soil material and a completely planar surface develop. However, when runoff commences, some of the material transported to the depressions is transported downslope along the lines of flow that occur between the depressions. Once again, some of this material is moved as suspended load but, because shallow flows still occur at this stage, RIFT also contributes to the downslope movement of the soil material between and perhaps through the depressions. Once flow depths exceed one or two millimetres, very little downslope transport occurs in the splash produced by the raindrops impacting the flow (Moss and Green, 1983). Thus, because, once again, the flows often have low shear velocities, RIFT may be the major contributor to the downstream movement of the coarser material at this stage.

As flow velocities increase, the flow shear velocities may become sufficient to entrain some of the detached material lying on the bed. When

this occurs, some of the material previously moved downstream by RIFT is entrained in the flow but, since entrainment of the detached particles is flow velocity dependent and particle size selective, the larger, heavier particles may be moved by RIFT while somewhat smaller, lighter particles move as bed load and suspended load. Further increases in flow velocity may ultimately lead to the all material previously moved by RIFT becoming entrained by the flow. In simple terms, the contributions of the suspended load, bed load and RIFT to sediment transport by shallow rain-impacted flow can be expressed mathematically by

$$T_F = T_S + T_B + T_R \quad (1.1)$$

where T_F is the rate at which soil material is transported across any arbitrary boundary covered by the rain-impacted flow, and T_S , T_B and T_R are the contributions made by suspended load, bed load and RIFT respectively. It should be noted that, in this context, Eq. 1.1 does nothing more than identify that there are different masses of soil material moving at different rates via different transport processes. It does not imply that interactions between the transport processes do not occur. In fact, as discussed above and below, certain interactions are known to occur.

Further increases in flow velocity can lead to the flow shear velocities exceeding the critical velocities required to detach soil material from the soil matrix. When this occurs, T_R tends towards zero because the flow can usually transport most of the detached material without the aid of raindrop impact. Raindrop impact may still aid erosion by detaching additional soil material from the soil matrix within the flow line. However, scouring by flow often leads to channels (e.g., rills) developing on the surface, and the increased flow depth that results may reduce the ability of the drop impacts to detach material within the channel. Although RIFT may not persist within the immediate area of the scour, it may still be extremely important in transporting material to the flow line. Concentration of the flow into channels results in a general reduction of flow depth in the areas between the channels thereby encouraging RIFT in the inter-channel (inter-rill) areas. The amount of scour that can occur within the channel is controlled by the difference between the amount of material fed into the channel from the inter-channel areas and the transport capacity of the flow in the channel (Foster, 1982). Consequently, RIFT in the inter-channel areas can have a major

influence on the channel morphology as well as influence the movement of detached material within the inter-channel areas. Once developed, rill geometries may stabilize as scouring diminishes, particularly if rainfall rate and, hence, flow discharge falls. Although RIFT may not prevail within channels during their development, RIFT may occur within the rills when shallow flows occur as flow discharges rise and fall in response to temporal variations in the rainfall rate.

1.2 THE SCOPE OF THE WORK BEING REPORTED

As discussed above, RIFT may dominate sediment transport when erosive waterdrops impact shallow flows over surfaces containing detached material that cannot be entrained by the flow. Although it has been long recognised that raindrops enhance the movement of sediment when they impact shallow flows, little quantitative research has been done on the factors that influence RIFT. Obviously, because RIFT involves interactions between raindrop impact, surface-water flows and particles lying on the surface beneath these flows, factors such as drop size, drop velocity, flow depth, flow velocity, particle size, shape and density must have some influence on RIFT. Consequently, the aim of the research reported here is to examine the role of these factors on RIFT. Since RIFT is a process which transports soil materials downstream after they have been detached from the soil matrix, the experiments reported here are based on laboratory experiments that involve eroding surfaces made up almost exclusively of non-cohesive material. The experiments are restricted to

- (a) flow depths where splash does not contribute significantly to the transport of sediment across any arbitrary boundary over which the surface water flows,

and

- (b) flow velocities which are less than the critical velocities required to entrain the detached material when no drop impacts occur.

This ensures that all the interactions between raindrop impact, the surface-water flow and the underlying surface are devoted entirely to RIFT in the situations being investigated.

As an erosion process, RIFT has not been widely studied and a well established theory for sediment transport by rain-impacted flow does not yet

exist. Consequently, a theory for RIFT is developed here in Chapter 2. The erosive effect of certain interactions between the impacting raindrop, the surface-water flow and the eroding surface cannot yet be readily ascertained from basic physical principals. In Chapter 3, the effects of factors such as flow depth and velocity, particle size and density, drop size and velocity on RIFT are examined in a series of experiments.

Although the experiments reported show that flow depth and velocity are important factors in erosion by rain-impacted flow, they are factors that are not often measured in experiments. Thus, in Chapter 4, a simplified model of erosion by rain-impacted flow is developed using more commonly measured parameters, and then the model is used to illustrate the result of ignoring the effect of flow in interrill and sheet erosion areas. Finally, in Chapter 5, suggestions on areas of further study are presented.

CHAPTER 2

THEORIES RELEVANT TO EROSION BY RAIN-IMPACTED FLOW

Many experiments involving the application of rainfall, both natural and artificial, on small areas of soil have been made in many parts of the world. Rain-impacted flows have commonly occurred in many of these experiments but, in some cases, (e.g., Wang, 1988), raindrop splash has also contributed significantly to the transport of soil material from the eroding area. In these cases, the rate (T) sediment is transported across a unit width of any arbitrary boundary can be expressed by

$$T = T_F + T_A = T_S + T_B + T_R + T_A \quad (2.1)$$

where T_A is the contribution made by drop splash and T_S , T_B and T_R are the contributions made by suspended load, bed load and RIFT to T_F as defined in Eq. 1.1. With 4 possible modes (splash, suspended load, bed load and RIFT) of transport, and spatial and temporal changes in the dominance of particular modes, many of the experiments that have been done so far have not produced widely applicable relationships between T and many of the factors upon which it depends. However, when flows are not concentrated but spread thinly over the soil surface, the detachment of soil particles from the soil surface results largely from the expenditure of raindrop energy (Meyer, 1981). Thus, under certain circumstances, empirical relationships exist between soil loss and factors such as rainfall intensity and rainfall kinetic energy.

2.1 EMPIRICAL RELATIONSHIPS

Despite the existence of 4 possible modes of transport in rainfall erosion, Meyer (1981) showed that, when drop impact dominates detachment on the slope lengths and gradients common in ridge furrow cultivation,

$$T = K R^w \quad (2.2)$$

where R is rainfall intensity, K is a coefficient that varies between soils and w is a power which may vary between soils but is usually close to 2. Foster (1982) proposed that Eq. 2.2 with $w=2$ should be used to account for the

effect of raindrop impact in models of rainfall erosion. Many models currently being used or developed are based on Foster's proposal. These models do not attempt to identify the individual contributions made by any of the 4 transport modes to soil eroded from inter-channel areas.

Although K is influenced by soil characteristics, K is not a fundamental soil property in any sense (Nearing et al., 1990). Experimental data are available that indicates that K is influenced by a number of non-soil factors such as flow depth (e.g., Palmer, 1963; Moss and Green, 1983; Mutchler and McGregor, 1983; Kinnell, 1990a, 1990b), flow velocity (e.g., Moss, 1988; Kinnell, 1990a, 1990b), drop size (e.g., Moss and Green, 1983; Kinnell, 1990a), and drop velocity (e.g., Kinnell, 1990b). Slope gradient has been shown to influence K (Meyer and Harmon, 1989) but, as will be discussed later, the effects associated with slope gradient result from the variations in flow depth and velocity that are induced by changes in slope gradient. Some consideration of the protective effect of surface vegetative cover may be necessary in some circumstances (Rose et al., 1983; Rose and Hairsine, 1988). Factors such as cohesion and soil particle characteristics such as size, shape, and density, are the primary soil factors that have been observed to influence K . According to Rose et al. (1983), the measurement of the fall velocity of the particles in water provides the means of accounting for the effect of changes in the particle characteristics.

2.2 THE ROSE et al. THEORY

The rate sediment is transported across a unit width of any arbitrary boundary (q_s) is given by

$$q_s = q_w c \quad (2.3),$$

where q_w is the rate water is discharged across a unit width of the boundary, and c is the sediment concentration (the mass of sediment discharged per unit mass or volume of water).

Rose et al. (1983) considered that three processes are active in rainfall erosion:

- (i) rainfall detachment, in which raindrops splash sediment from the soil surface into the water of overland flow;
- (ii) sediment deposition, which is the result of sediment settling out under the action of gravity; and
- (iii) entrainment of sediment, the process whereby overland flow picks up sediment from the soil surface, whether in rills, between rills, or in sheet flow without rills.

According to Rose et al. (1983), mass conservation of sediment of size range class i requires that

$$\frac{\partial}{\partial x}(q_w c_i) + \frac{\partial}{\partial t}(h c_i) = e_i - d_i + r_i \quad (2.4)$$

where h is flow depth, e is the rainfall detachment rate, d is the sediment deposition rate and r is the sediment entrainment rate.

One of the purposes of the Rose et al. theory is to separate of the effect of raindrop impact from the effect of flow shear. In terms of the effect of drop impact, this theory is based on the concept that detached material contained in drop splash is an important contributor to the material yielded to the transport system provided by overland flow. For bare soil surfaces,

$$e_i = a C_e \frac{R^p}{I} \quad (2.5)$$

where a is a measure of the detachability of the soil by rainfall, C_e is the fraction of the soil unprotected from raindrop detachment, R is rainfall intensity, p is an exponent thought, at that time, to be close to 2, and I is the number of sediment size classes. I appears in Eq. 2.5 as the result of the stipulation that $c_i = c/I$. In this model, deposition is considered in terms of

$$d_i = v_i c_i \quad (2.6).$$

where v_i is the mean fall velocity in water of the particles in size class i . According to Rose et al., the solution for c_i in the ordinary differential equation that results from Eqs. 2.4 to 2.6 and $r_i=0$ is

$$c_i = \frac{a C_e R^p}{I(Q + v_i)} \quad (2.7),$$

where Q is the rain induced discharge of water per unit area. Frequently the effect of Q is negligible because often $v_i \gg Q$ (Rose et al., 1983).

Originally, Rose et al. considered the raindrop effect only in terms of drop splash when they developed Eq. 2.4. Now (Rose and Hairsine, 1988), the definition of e implies that e represents the rate by which material detached by drop impact enters the flow both aerially by splash and directly by uplift from the surface underlying the flow. Also, the possibility that p is unity is now considered (Rose and Hairsine, 1988).

According to Rose and Hairsine (1988), a is known to depend on soil type and condition, the depth of the water layer above the surface, and $C_e^\#$. Also, when RIFT occurs over cohesive material, non-cohesive material is deposited over the cohesive material before being transported downstream by a subsequent drop impact (Kinnell, 1990a). This deposited material may form a layer that shields the underlying cohesive material from the force of drop impacts. The effect of this deposited layer on a can be considered in terms of a shielding coefficient (H^\clubsuit) that results from concepts developed by Hairsine (1988). It follows from Proffit et al. (1989), who used Hairsine's concepts, that

$$a = H a_D + (1-H) a_M \quad (2.8)$$

where a_D is the value of a for the deposited (non-cohesive) layer and a_M is the value of a for the underlying usually cohesive soil matrix. Hairsine and Rose (1990) observed that, for $h > h_*$,

Since C_e was considered explicitly in the model described by Rose and Hairsine (1988), saying that a depends on C_e appears to be an error in this Rose-Hairsine paper

♣ In this thesis, H is the degree of protection provided by the deposited layer and it depends on both the thickness and the proportion of the bed covered by the deposited layer. Originally, Hairsine (1988) considered H to be only related to the proportion of the bed covered by the deposited layer.

$$a_X = a_{X*} (h_* h^{-1})^b \quad (2.9),$$

where a_X is either a_D or a_M , h is flow depth, h_* is the critical flow depth below which a_D remains constant and equal to a_{D*} , and b is an exponent.

Hairsine and Rose (1990) concluded that H is usually less than one because erosion of the deposited layer must eventually lead to detachment occurring from the underlying layer. However, $H=1$ probably applies to raindrops impacting flows over beds of loosely packed uniform sized particles, a common situation in the experiments with beds non-cohesive material that are considered later in Chapter 3. In the situation where the non-cohesive deposited layer completely shields the underlying material, it follows that

$$c_i = \frac{a_{D*} h_*^b R^D}{h^b \sum_{i=1}^I \alpha_i v_i} \quad (2.10).$$

where α_i is the ratio of the concentration next to the bed to the mean concentration over the entire depth (Hairsine and Rose, 1990).

2.3 THE KINNELL THEORY FOR RIFT

The theory presented above considers the effect of some of the detachment and deposition processes on the sediment transport rate (q_s) through the effects of these processes on the sediment concentration (c). The possible effects of changes in raindrop characteristics (such as size and velocity) on c were not considered directly by Rose et al. (1983) in developing their theory although these effects could be considered through the term a . However, another approach would be to consider the direct effects of the detachment and deposition processes on q_s rather than c . This approach was adopted by Kinnell (1990a). As will be seen later, eliminating the need to consider c in the determination of c_s eliminates certain complications that arise from the fact that, because $c=q_s/q_w$ and q_w is equal to the product of flow depth (h) and velocity (u), there is some inherent covariance between c and h .

Consider an arbitrary boundary orthogonal to the direction of a laminar low velocity flow at any arbitrary point x on a plane surface. Consider a particle, such as one moved to the flow by splash, entering a tranquil flow at its surface (Fig. 2.1A). As the particle falls through the liquid, it strives to acquire its terminal velocity of fall in water (v_p). This velocity varies with particle characteristics such as particle size (p), shape and density, and the time the particle is suspended in the flow (t_p) is given approximately by

$$t_p = \chi h v_p^{-1} \quad (2.11).$$

where χ , the ratio of v_p to the average velocity of fall of the particle through the flow, is assumed to be one. As the particle falls through the flow, it is subjected to horizontal forces resulting from the motion of the flow, and it rapidly acquires the horizontal velocity of the fluid through which it falls. Because, in laminar flows, flow velocities vary vertically through the flow (Chow, 1959), the particle falls with a non-linear trajectory. However, because the vertical velocity of the particle remains approximately constant during its fall, the horizontal distance travelled by the particle while it is suspended in the liquid (x_p) varies directly with t_p and the depth-averaged flow velocity (u);

$$x_p = t_p u \quad (2.12).$$

For a particle to reach the boundary at x , it must enter the flow at a distance x_p upstream of the boundary (Fig. 2.1A). Any particle entering the flow at an upstream distance greater than x_p will be deposited on the surface upstream of x .

In flows that are unable to entrain loose particles lying on the surface over which they flow, the downstream movement of particles falling to that surface is not sustained once the particle reaches the surface. A subsequent lift force has to be applied to continue the downstream movement and this force is provided by raindrops impacting the flow when RIFT occurs. When an erosive rain or water drop impacts a shallow surface-water flow, it can cause a cloud of particles to be suspended in the flow (Moss and Green, 1983). As in the case of a particle entering the flow at its surface, the particles in the cloud move downstream during their fall. The distance moved downstream again depends on the time the particles remain suspended in the flow and the velocity of the fluid through which the particles fall. If, for simplicity,

FIG. 2.1

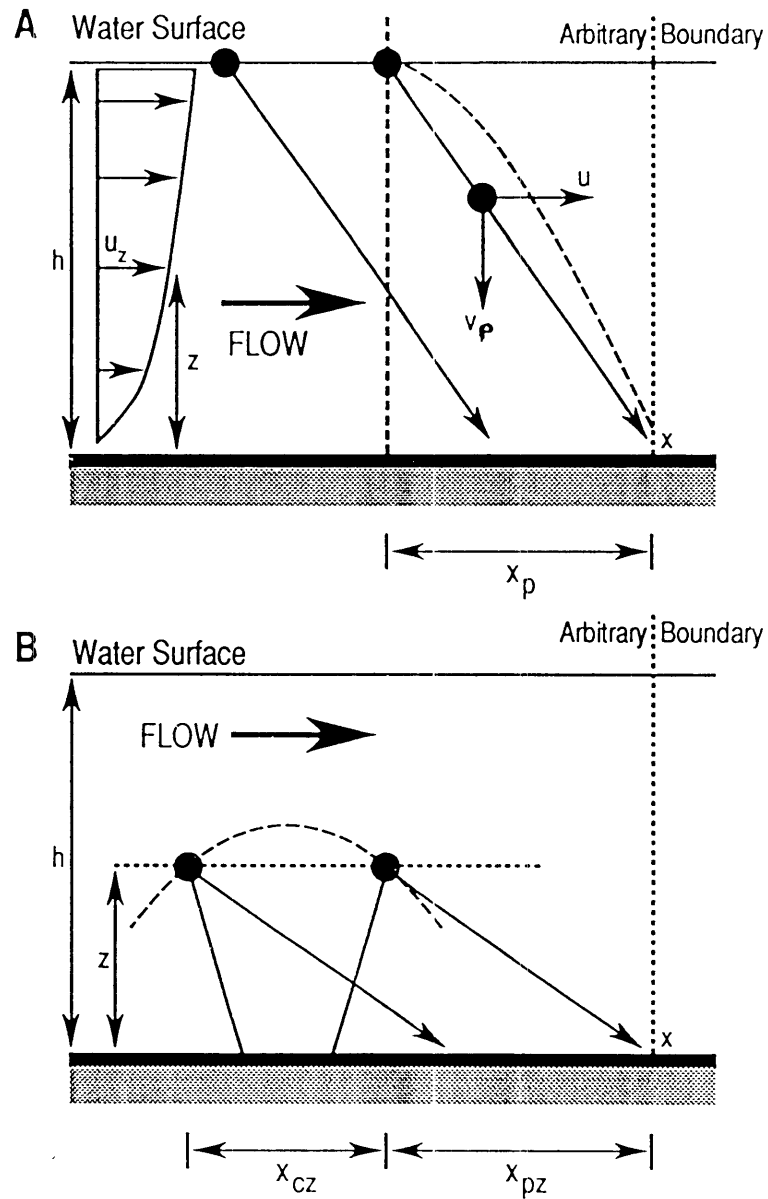


Figure 2.1. Schematic representation of the lateral movement of particles falling through a laminar flow after A) entry at the water surface and B) uplift due to drop impact. The upper boundary of the particle cloud is indicated by the dashed line. x_{cz} is the diameter of the cloud at the height z above the bed

the average flow velocity experienced by a particle during its rise and fall is assumed to be equal to u , then Eq. 2.12 applies but t_p will depend on the height to which the particle is lifted (z) in the flow, not h . If, again for simplicity, the rise is considered to be very much more rapid than the fall, then

$$t_p \approx t_{pz} = \chi z v_p^{-1} \quad (2.13),$$

where t_{pz} is the time taken for the particle to fall from the height z to the underlying surface. It follows from Eq. 2.13 that, for a particle lifted to a height z to reach the boundary at x , it must reach that height z at a distance x_{pz} upstream of the boundary (Fig. 2.1B). It also follows that if all the particles with a given fall velocity rising to the height z are to pass across the boundary, the drop impact producing the cloud must occur within the distance $x_{pz} - 0.5x_{cz}$ of the boundary where x_{cz} is the diameter of the cloud of particles at the height z .

If we consider rain of uniform drop size (d) impacting flows over a surface of p sized particles all of which have the same fall velocity (v_p), then it follows from the above that

$$M_{Dz} [p, d] = f_d D_{pdz} \quad (2.14)$$

where M_{Dz} is the mass of the particles which, after being lifted to a height z , are transported across the boundary in unit time, f_d is the frequency of the impact of the drops within the distance $x_{pz} - 0.5x_{cz}$ of the boundary and D_{pdz} is the mass of the particles lifted to the height z by each drop impact. Figure 2.2 illustrates the effect of x_{pz} on f_d . Although it was implied above that f_d varies directly with $x_{pz} - 0.5x_{cz}$, it is evident from Fig. 2.2 that there is no need to consider x_{cz} when $x_{pz} > x_{cz}$. Because of the random temporal and spatial nature of raindrop impact, the amount of material in the part of any cloud that extends upstream beyond the distance x_{pz} from the boundary (e.g., D_4 , Fig. 2.2C) is offset by the impacts of drops immediately upstream of distance x_{pz} extending their clouds downstream within the distance x_{pz} of the boundary (e.g., D_5 , Fig. 2.2C). In simple terms, x_{pz} determines the upstream extent of an active zone that exists upstream of the boundary for impacts causing particles to rise to the height z . Impacts within the active zone effectively cause particles lifted to the height z to immediately pass

FIG. 2.2

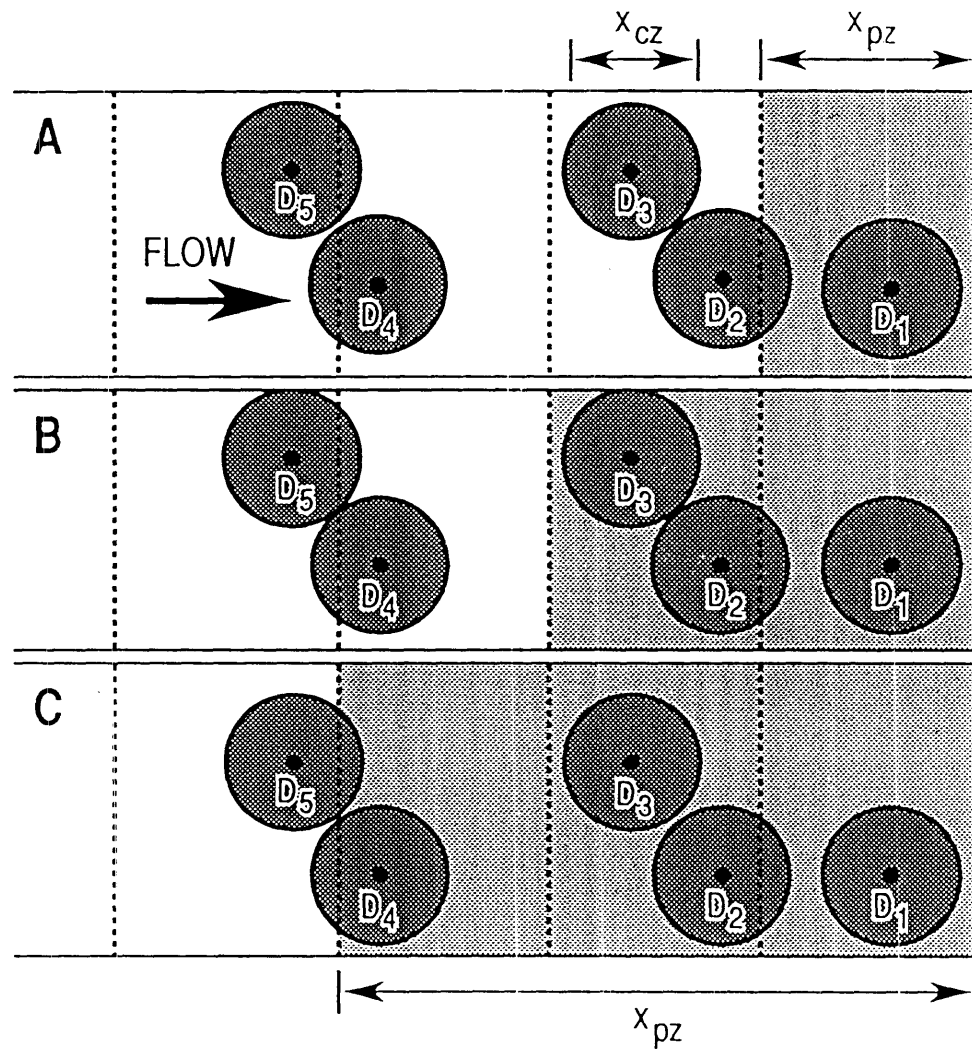


Figure 2.2. Schematic plan view of the effect of varying particle travel distance (x_{pz}) on the rate of transport of particles uplifted into the flow by drop impact. Each frame (A,B,C) shows the spatial distribution and extent of the clouds at the height z (see Fig.2.1B) produced by the impact of drops (D_1 - D_5) in some arbitrary element of time.

across the boundary. Impacts upstream of the active zone cause particles to move towards and into the active zone where they must wait for a subsequent impact before passing across the boundary.

Figures 2.1B and 2.2 consider the case when $x_{cz} < x_{pz}$. There are situations, particularly when flow velocity is low, when x_{cz} may be greater than x_{pz} . In these situations, only part of the cloud of particles produced by any drop impacting upstream of x can be deposited beyond the boundary. At any point x' upstream of the distance $0.5x_{cz}$ of the downstream end of an eroding area, the effects of the impacts either side of the boundary noted in Fig. 2.2C maintain a linear relationship between f_d and x_{pz} . For points closer to the downstream end, the balance between impacts on the upstream and downstream sides of the boundary is lost. However, consideration of formulas for calculating the area of a segment of a circle indicates that, if the particles at the height z are distributed relatively uniformly within the part of the cloud being considered, the combined effect of x_{pz} changing the frequency of the drop impacts that cause particles to immediately pass across the boundary and the changing proportion of the cloud passing beyond the boundary will tend to maintain a close to linear dependence of f_d upon x_{pz} at low flow velocities. Consequently, in gross terms,

$$M_{Dz} [p, d] = F_d x_{pz} D_{pdz} W_f \quad (2.15),$$

where F_d is the spatially averaged impact frequency for drops of size d and W_f is the width of the flow covered surface in the active zone that extends a distance x_{pz} upstream from the boundary. It should be noted that erosive drops impacting immediately upstream of any boundary will cause part of the cloud to pass "downstream" across a boundary even when the flow velocity is zero. Consequently, $M_{Dz} > 0$ when $u = 0$ will occur at the downstream end of an eroding area.

F_d varies directly with rainfall intensity and inversely with drop volume so that

$$M_{Dz} [p, d] = \frac{6 R_d x_{pz} D_{pdz} W_f}{\pi d^3} \quad (2.16),$$

where R_d is the intensity of rain of drop size d . It follows from Eqs. 2.12, 2.13 and 2.16 that

$$M_{Dz} [p, d] = \frac{6 R_d t_{pz} u D_{pdz} W_f}{\pi d^3} \quad (2.17),$$

and, because the mass of material moved by a drop impact is the sum of the masses of material in the cloud at various heights above the soil surface,

$$M_D [p, d] = \frac{6 R_d t'_{pd} u D_{pd} W_f}{\pi d^3} \quad (2.18)$$

where M_D is the mass of material moved across the boundary in unit time by the impact of the drops, D_{pd} is the mass of material lifted into the flow by a drop of size d impacting in the active zone, and

$$t'_{pd} = \frac{\int_0^{zh} (t_{pz} D_{pdz}) dz}{D_{pd}} \quad (2.19).$$

where zh is the height of the top of the cloud of particles. The product of t'_{pd} and u can be regarded as the effective average travel distance (x'_{pd}) of the particles in the cloud. If q_{SR} is the sediment transport rate produced by RIFT per unit width of the flow, it follows from Eq. 2.18 that

$$q_{SR} [p, d] = \frac{6 R_d t'_{pd} u D_{pd}}{\pi d^3} \quad (2.20).$$

The rate (q_w) water flows across a unit width of a boundary is given by

$$q_w = hu \quad (2.21).$$

Thus, it follows from this, Eq. 2.20 and the definition of sediment concentration (= mass of soil material per unit volume or mass of water discharged) that

$$c_R [p,d] = \frac{q_{SR} [p,d]}{q_w} = \frac{6 R_d t'_{pd} D_{pd}}{\pi d^3 h} \quad (2.22),$$

where c_R is the sediment concentration produced RIFT.

Equations 2.20 and 2.22 are based on relatively simple concepts. Despite this, there are a number of experimental results that support them. Equation 2.20 indicates that, when RIFT is dominant, the transport rate should vary directly with flow velocity while Eq. 2.22 indicates that the sediment concentration generated by drops impacting flows should vary independently of flow velocity. Equation 2.22 is consistent with the results of Kinnell (1988) for 2.7 mm drops impacting flows over 0.2 mm sand. Kinnell observed that the c_R to flow depth (h) relationship was not influenced by flow velocity (u) varying between 9 and 182 mm s⁻¹ over beds of 0.2 mm sand. Equation 2.20 is also consistent with the results of Moss (1988). Moss measured the sediment transport rates produced by rain of uniform drop size when drops of various sizes (0.81 mm, 1.27 mm, 2.7 mm, 5.1 mm) impacted flows with a number of flow depths (3 mm, 6 mm, 10 mm) over 0.2 mm sand and a range of flow velocities similar to that used by Kinnell. As can be seen from Fig. 2.3, the relationships between q_{SR} and u were linear, or close to linear, in the majority of the situations examined by Moss. There is evidence of non-linearity at low flow velocities when the smaller ($d < 2.7$ mm) drops impact flows deeper than $3d$ but, when considered in terms of Fig. 2.2 and Eq. 2.20, this non-linearity could result from the failure of the smaller drops to lift particles up high enough for them to attain an average horizontal velocity close to the depth-averaged flow velocity (u) upon which Eq. 2.20 is based. The larger drops are more likely to distribute particles throughout the depth of flow particularly when they penetrate down to the bed during the impact. However, as will be discussed later, considerable temporal and spatial variation exists in the type of rainfall system used by Moss so that the non-linearities that can be seen in Fig. 2.2 may be artifacts.

Equations 2.20 and 2.22 do not specifically consider the influence of flow turbulence and interactions between raindrop impacts. The product of t'_{pd} and u gives the effective average distance (x'_{pd}) a particle travels after being lifted from the bed by a drop impact. Visual observation of the results of the impact of single drops into flows over 0.2 mm sands indicated that, for

FIG. 2.3

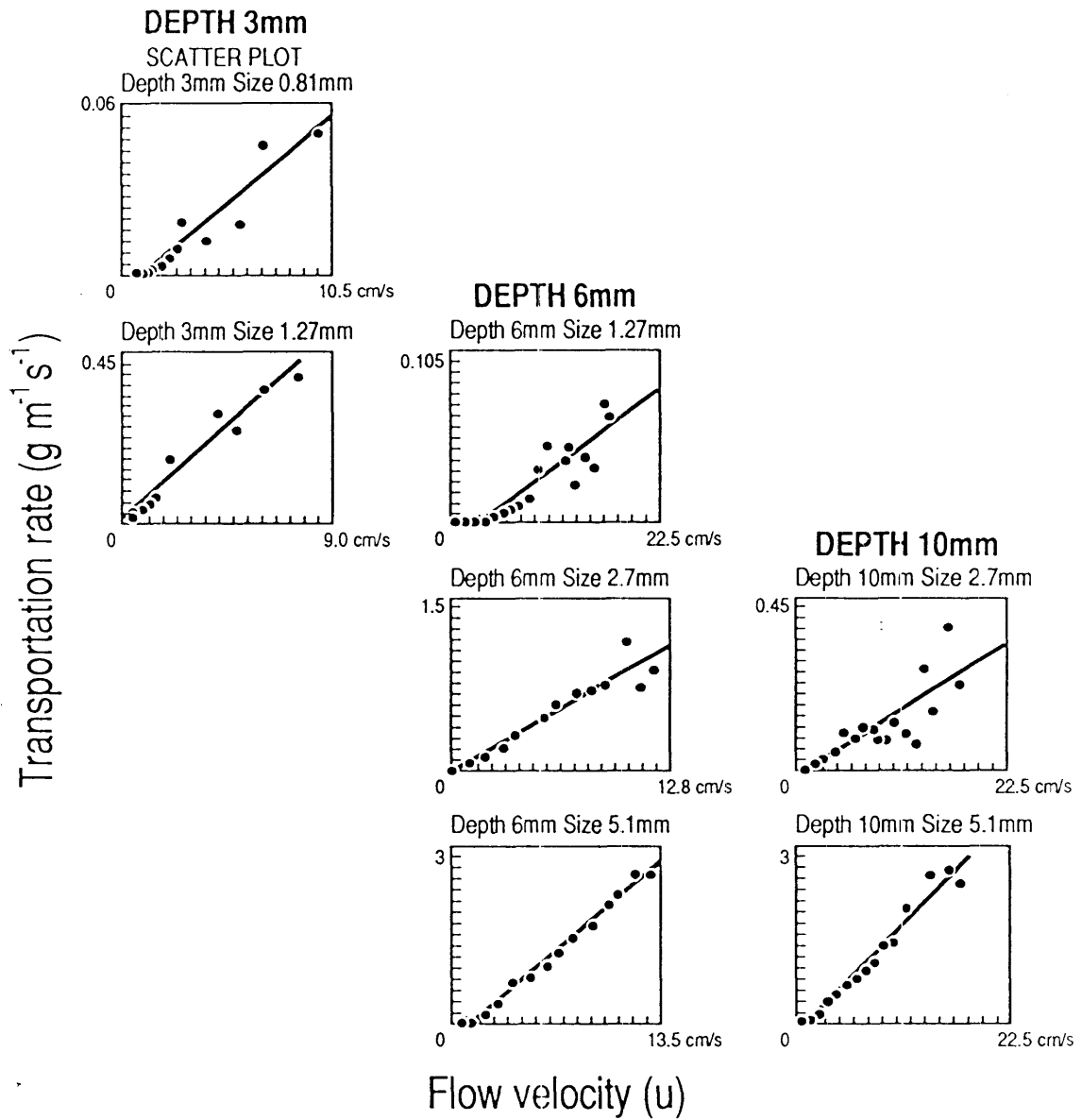


Figure 2.3. The relationship between the transport rate of sediment and flow velocity for drops of various sizes impacting flows of various depths in the experiments of Moss (1988). The rainfall intensity was 64 mm hour^{-1} in all cases.

$d=5.1$ mm, $v_d = 8.95$ m s⁻¹, $h=5$ mm, $p=0.2$ mm, t'_{pd} had a magnitude of about 0.6 s (Kinnell, 1990c). Thus at $u=20$ mm s⁻¹, the 5.1 mm drops cause 0.2 mm particles to travel about 12 mm between the drop impacts in 5 mm deep flows. At $R_d=64$ mm h⁻¹, each drop formed in the rain modules used by Moss (1988), Kinnell (1988) and in the experiments reported later produces, on average, a 5.1 mm drop every 6 s, and a 2.7 mm drop every 0.9 s. Consequently, in many experiments, each drop impact probably produces an individual "event" that is affected little by other drop impacts that may be close temporally or spatially.

Moss suggested that the linearity in his q_{SR} to u relationships resulted from the ability of the flow to increase the duration of the turbulence produced by a drop impact as flow velocity increased. Although Eqs. 2.20 and 2.22 were developed without considering prolonged or persistent turbulence, the turbulence described by Moss can be considered in terms of its effect on t'_{pd} . Consequently, even if, as suggested by Moss, there is a change of regime as flow velocity increases, Eqs. 2.20 and 2.22 can also be applied to the second regime although the values of t'_{pd} may differ from those obtained for non-turbulent flow.

Equations 2.20 and 2.22 also indicate that both q_{SR} and c_R should vary directly with rainfall intensity. The results of unpublished experiments by Moss (Table.2.1) support this for erosion on loose level surfaces. Results such as those obtained by Walker *et al.* (1978) appear to indicate that q_{SR} varies with rainfall intensity to a power close to 2 for flows over inclined surfaces of sand. However, the effect of u on q_{SR} was not considered in the analysis performed by Walker *et al.* and, as can be seen from Fig. 2.4, the results for their experiments are in concert with the theory presented here. Flow depth explicitly influences c_R (Eq. 2.22) because $q_w=hu$ but variations in flow depth will also influence c_R through the ability of the water layer to dissipate raindrop energy. However, relatively minor variations in flow depth were observed to occur as flow discharge varied in response to the changes in rainfall intensity in the Walker *et al.* experiments, and this helped to maintain a high degree of linearity in the c_R to R_d relationships shown in Fig. 2.4. The difference in the regression coefficients for the c_R to R_d relationships shown in Fig. 2.4 can be interpreted as resulting from gross differences in flow depth between the two slope gradients used in the Walker *et al.* experiments. As shown in Fig. 2.5, which results from the experiments

Table 2.1 Regression analysis for the effect of rainfall intensity (R_d in mm h^{-1}) on q_{sR} ($g\ m^{-1}s^{-1}$) for 0.2 mm sand when raindrops impacts flows over 0.2 mm sand after 11.2 m fall. Data from Moss (pers.comm).

LINEAR REGRESSION $q_{sR}(d) = k_1 R_d$						
d drop size (mm)	h flow depth (mm)	u flow velocity (mm.s ⁻¹)	k_1	r^2 corr	df	signif
5.1	6	51	0.0144	0.96	11	1%
2.7	6	51	0.0073	0.94	7	1%

FIG. 2.4

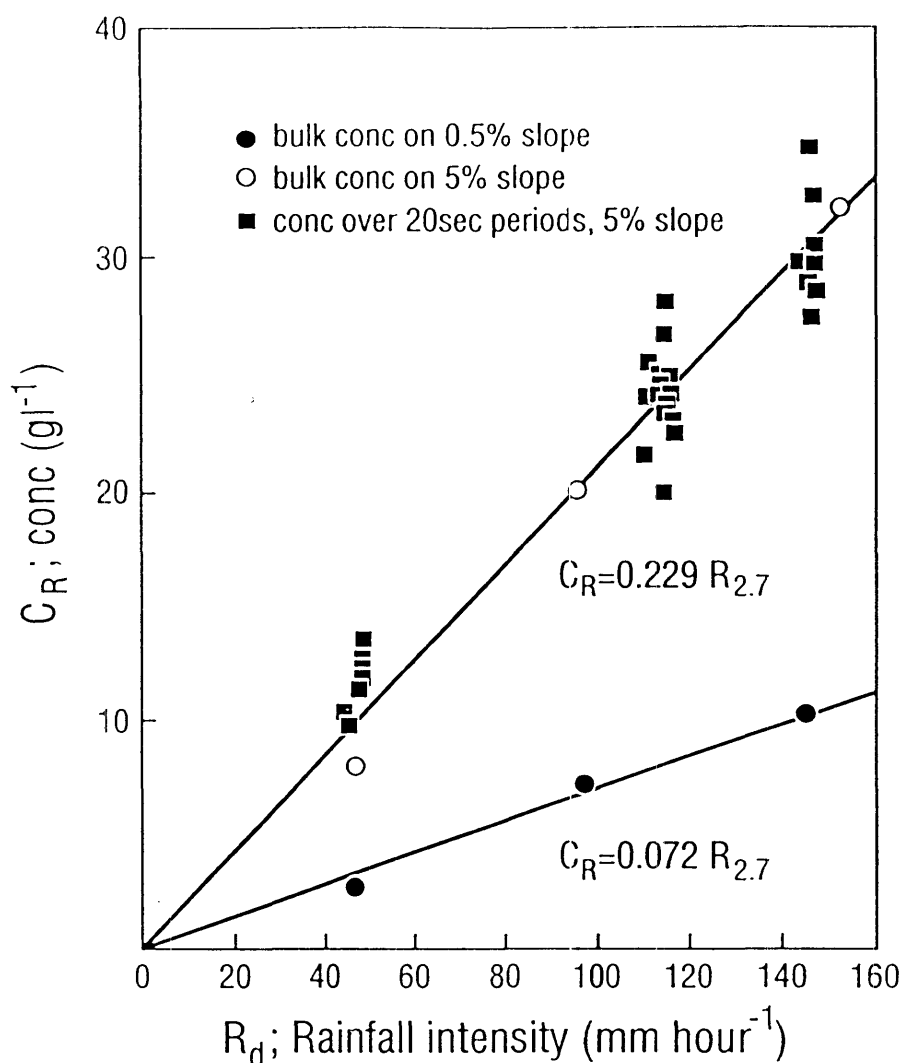


Figure 2.4. The relationship between rainfall intensity and the sediment concentration produced by 2.7 mm drops impacting flows over 3 m long sand surfaces inclined at 0.5 % and 5 % in the experiments of Walker et al. (1978). Bulk sediment concentrations were calculated by dividing the total mass of sand passing over the downstream end of the surface by the total volume of water discharged during the experiment. The short-term (20 sec) concentrations were obtained during an experiment where rainfall intensity was varied in a cyclical manner over a period of time. For these data, it is likely that flow depths were not steady between many of the samples collected at a given rainfall intensity.

FIG. 2.5

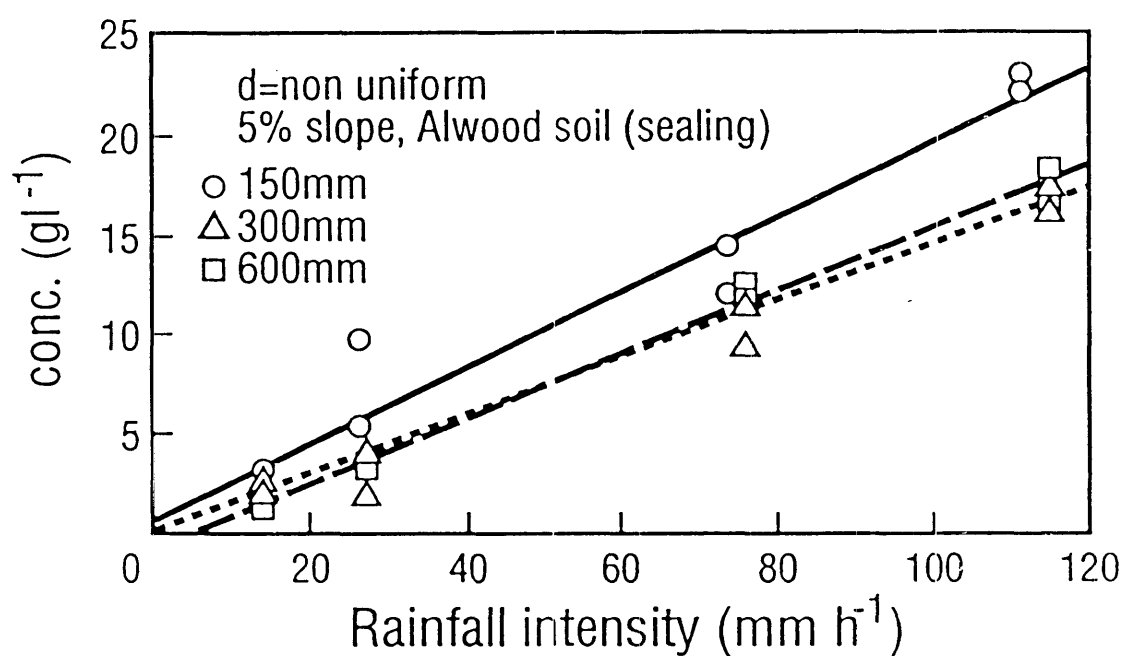


Figure 2.5. The effect of rainfall intensity on the sediment concentrations obtained when rain of non-uniform drop size impacted shallow flows over soil surfaces in the experiments of Meyer and Harmon (1989) where slope lengths varied from 150 mm to 600 mm.

of Meyer and Harmon (1989), linear relationships between c_R and R (d =non-uniform) also occur when rain-impacted flows erode soil surfaces. In general, the available data support Eqs. 2.20 and 2.22 and, hence, the theory which led to their development.

It should be noted that rewriting Eq. 2.22 in terms of an expression for c_i yields

$$c_i(d) = \frac{6 R_d t'_{pd} D_{pd}}{\pi d^3 h} \quad (2.23)$$

where p is the median (or perhaps modal) size of the particles in class i . Equation 2.23 differs from Eq. 2.10 in that it considers not only rainfall intensity but other rainfall characteristics which influence RIFT. Also, the structure of Eq. 2.23 enables the effect of flow depth on factors such as D_{pd} and t'_{pd} to be considered separately from the effect of h on q_w . In comparison, Eq. 2.10 does not distinguish between the effect of flow depth on the ability of the drops to temporarily suspend particles in the flow and the fact that $q_w=hu$.

2.4 THE ROLE OF PRE-DETACHED PARTICLES IN RIFT OVER SOIL SURFACES

On soil surfaces, drop impacts may lift both pre-detached particles sitting on the soil surface and particles from the soil matrix. The pre-detached particles are lifted up into the flow first and particles are detached and lifted from the soil matrix only if energy is left over from this process. Thus, the pre-detached particles have a protective effect. If H is the degree of protection (0-1) provided by the pre-detached particles then it follows from Proffitt et al. (1989) that

$$D_{pd} = H.D_{pd,D} + (1-H)D_{pd,M} \quad (2.24)$$

where $D_{pd,D}$ is the value of D_{pd} when the pre-detached particles completely protect the soil matrix and $D_{pd,M}$ is the value of D_{pd} when no pre-detached particles protect the usually cohesive soil matrix. With only interparticle friction being present in loose non-cohesive material, $H=1$ occurs in many experiments, such as those of Moss and Green (1983), Moss and Green (1987),

Moss (1988) and Kinnell (1988) and here in Chapter 3, where loosely packed, uniform sized, non-cohesive material is used as the eroding surface. Values of H of the order of 0.9 can occur when rain from spraying rainfall simulators impacts flows over soil (Proffit et al., 1989, 1991). However, H is a dynamic factor and uncertainty about the value of H leads to uncertainty about the values of a_D and a_M (Eqs. 2.8-2.10) that have been determined so far (Proffit et al., 1989). Similar uncertainty will exist about the values of $D_{pd,D}$ and $D_{pd,M}$ if they are determined under similar conditions. The role of factors, such as x_p and the relative values of D_{pd} for the pre-detached and matrix particles, on H are illustrated here through the use of a mathematical model of the RIFT processes.

2.4.1 Modelling particle uplift, downstream movement and deposition

The computer model described here simulates the events that occur when drop impacts produce RIFT on a small planar surface such as that used in the experiments described by Kinnell (1990a) and in Chapter 3. Figure 2.1(B) provides a schematic cross section of particle movement resulting from a drop impact in RIFT. The computer model (Appendix I) is based on this scheme 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. 2.1(B), the cloud is depicted as being hemispherical. 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 cloud is considered to be flat and square with 18 mm sides. Also, in the model the particles remain suspended for 0.6 s so that $x'_{pd}=0.6u$. This is consistent with the observations reported by Kinnell (1990c) for 5.1 mm drops impacting 5 mm deep flows over 0.2 mm sand. Visual observation of the clouds that occurred during the experiments with 5.1 mm drops in Chapter 3 indicated that their maximum widths were about 20 mm when flows were about 5 mm deep.

The surface is assumed to be made up of 0.2 mm sized particles giving a population density of 25 particles mm^{-2} for each layer. Each drop impact is

assumed to disturb four layers of pre-detached particles so that a maximum of 100 particles can be lifted from each square millimetre disturbed. The area disturbed by a drop impact is assumed to be 9 mm x 9 mm. This is also consistent with observations of 5.1 mm drops impacting 5 mm deep flows.

In the computer program given in Appendix I, a 100 mm by 240 mm area is used. This area is considered to be made up of 1 mm square elements. The computer's inbuilt random number generator is used to determine the position of the drop impact within the 100 mm by 240 mm area.

In the program, particles pushed over a side boundary by drops impacting close to the side edges of the target are deposited in relevant positions on the other side of the target area. Thus the program effectively models the events that occur in part of a much wider area. Insufficient memory space is available in many MS-DOS based PC systems to simulate RIFT on the 500 mm by 500 mm area used in the experiments in Chapter 3.

Modelling the processes over non-cohesive material

When a drop impacts a flow over non-cohesive material such as the sand and coal used in Chapter 3, material eroded from the upstream end of the target is dispersed widely over the downstream end of the target (Fig. 2.6A). The movement of the eroded material is modelled by the computer program operating in its "source" mode. In this mode, the program keeps account of only the material that originates from the upstream end of the target. Despite its simplicity, the model is reasonably successful in reproducing the dispersion (Fig. 2.6B) of the material eroded from the upstream end of the target.

Modelling the processes over cohesive material

Consider a shallow flow over a soil surface that is totally free of detached particles. Consider a raindrop impacting that flow at some distance x upstream of the downstream boundary, and that x is many times the effective average travel distance (x'_{pd}) of the particles disturbed by a drop impact. In this circumstance, all of the particles detached from the soil matrix by the

FIG. 2.6

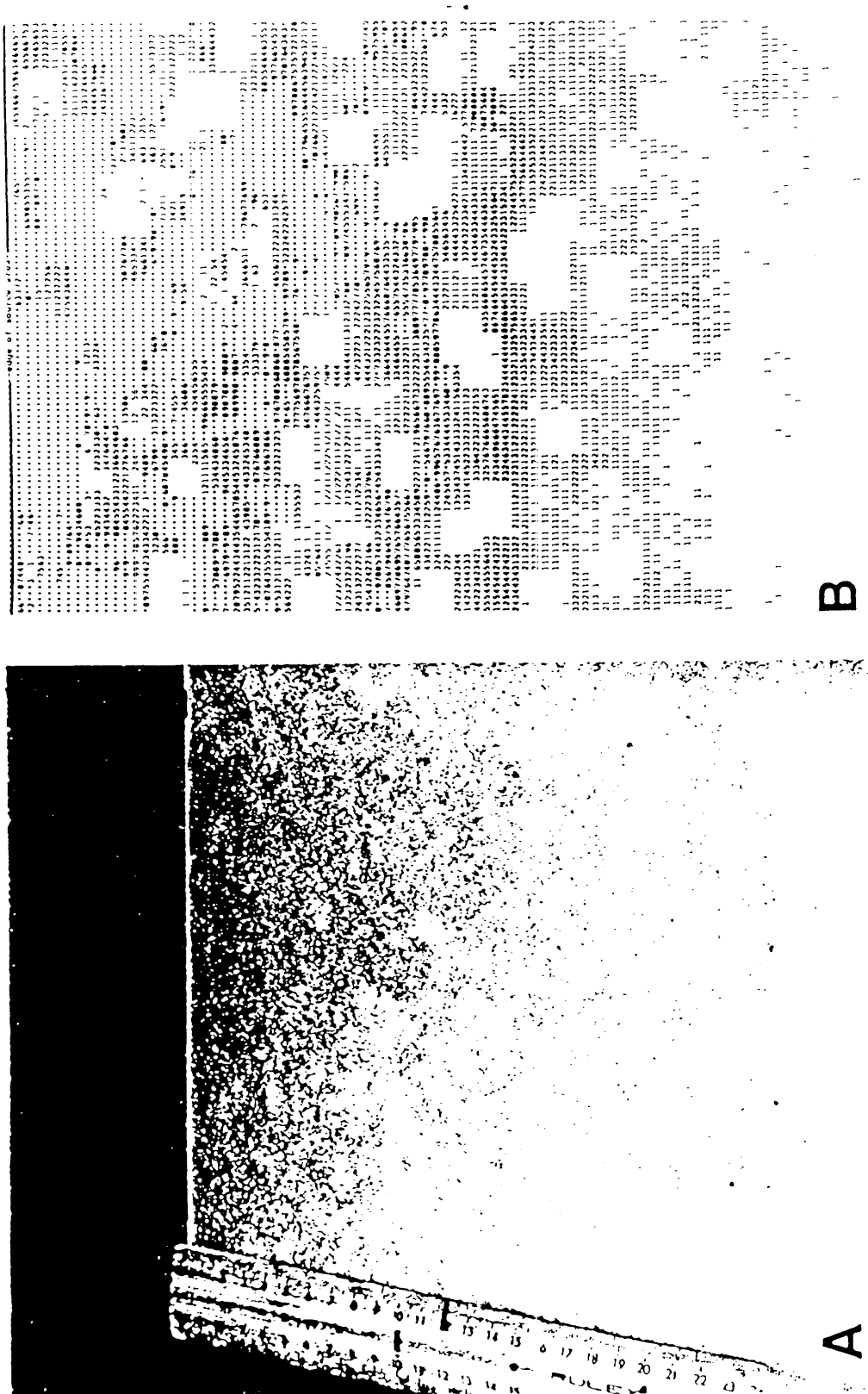


Figure 2.6. Distribution of material from a source area (top) over the downstream zone produced (A) in the experiment described in Section 3.3.7 and (B) by the simulation in Appendix I after 2000 drops impacted on an 100 mm wide by 250 mm long area. In (B) each digit indicates one tenth of the number of source particles per mm² in each 1 mm wide by 2 mm long element. * signifies 100 or more particles per mm², blank signifies less than 5 particles per mm².

FIG. 2.6

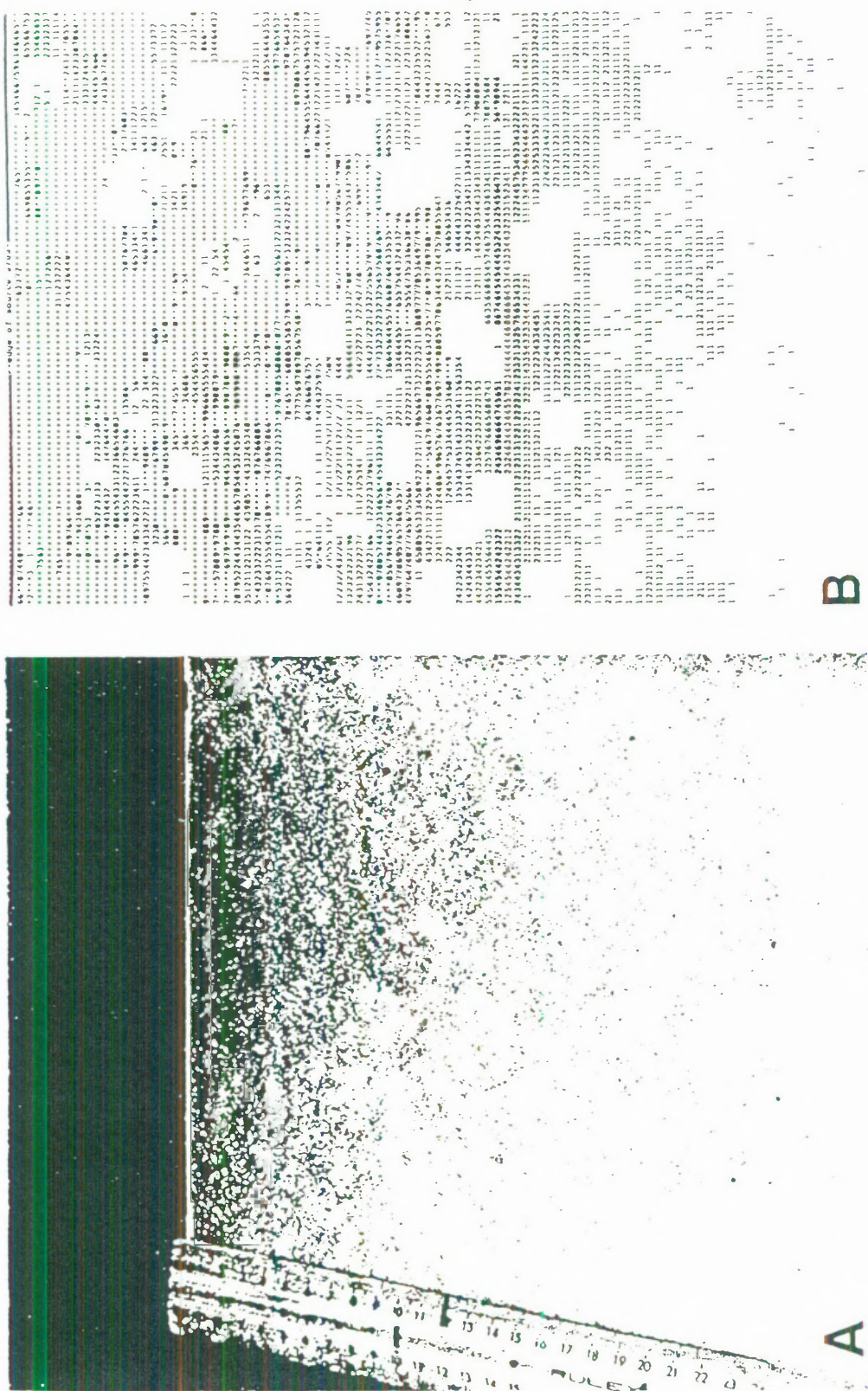


Figure 2.6. Distribution of material from a source area (top) over the downstream zone produced (A) in the experiment described in Section 3.3.7 and (B) by the simulation in Appendix I after 2000 drops impacted on an 100 mm wide by 250 mm long area. In (B) each digit indicates one tenth of the number of source particles per mm² in each 1 mm wide by 2 mm long element. * signifies 100 or more particles per mm², blank signifies less than 5 particles per mm².

drop impact are deposited on the soil surface downstream of x . Now consider the chain of impacts that moves the detached material downstream. The next impact at the distance x'_{pd} downstream from x first lifts the pre-detached particles up into the flow and then detaches more particles from the soil matrix. D_{pd} increases between the two drop impacts in the chain and, as a result, the amount of material deposited downstream of the second impact is more than was deposited at the second impact point, both in total and on a per unit area basis. The ability of a drop to deposit, on a per unit area basis, more downstream than was deposited at its point of impact is enhanced by the ability of neighbouring drops to feed detached material to the position of a subsequent impact in the chain. Consequently, as indicated schematically in Fig. 2.7, each subsequent impact in the chain of impacts that follows the first encounters more and more deposited material until all the material in the cloud generated by a drop impact comes from the deposited material and none from the underlying layer. When this occurs, D_{pd} reaches its maximum ($D_{pd,D}$). If $x'_{pd} \ll x$, then this is likely to occur well before the downstream boundary and, as a consequence, the drops impacting in the active zone transport only pre-detached particles across the downstream boundary. Thus, recalling that H denotes the ability of the deposited layer to shield the underlying material (Hairsine and Rose, 1990), this implies that $H=1$ may occur at the downstream end of an eroding area despite factors such as cohesion and interparticle friction limiting the amount of material lifted into the flow at x .

The program given in Appendix I simulates the movement of particles when drops impact flows over soil surfaces (cohesive materials) when it is operated in its "cohesive" mode. In the model the cohesive layer will yield, for the situation where no pre-detached particles exist, a user-selected proportion of the value of D_{pd} produced when the non-cohesive layer completely shields the cohesive layer. While the linkage of drop impacts in the movement of particles from some point upstream of the downstream boundary encourages D_{pd} to tend towards $D_{pd,D}$ as the distance from x increases, because raindrops impact the surface in a random manner, the simulation shows that the area of the soil surface that yields only pre-detached particles to RIFT develops in extent as time progresses. As shown by Figs. 2.8 and 2.9, the probability that D_{pd} for any given drop impact is at its maximum tends to decrease with distance upstream from the downstream boundary but increase with time. However, the average value of D_{pd} in this zone is below the maximum after a large number of

FIG. 2.7

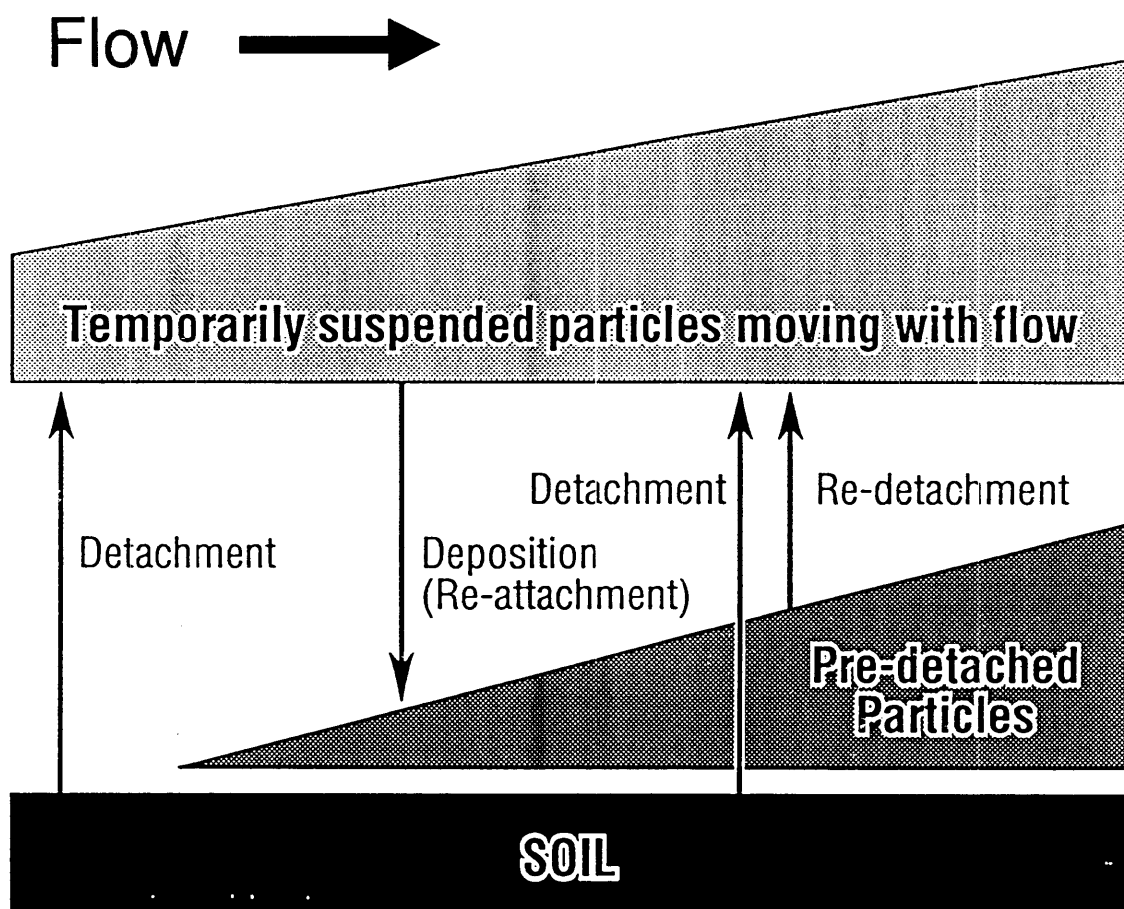


Figure 2.7. Schematic representation of the effect of detachment and deposition processes on the amount of material deposited on the bed and moving with the flow when RIFT occurs on soil surfaces

FIG. 2.8

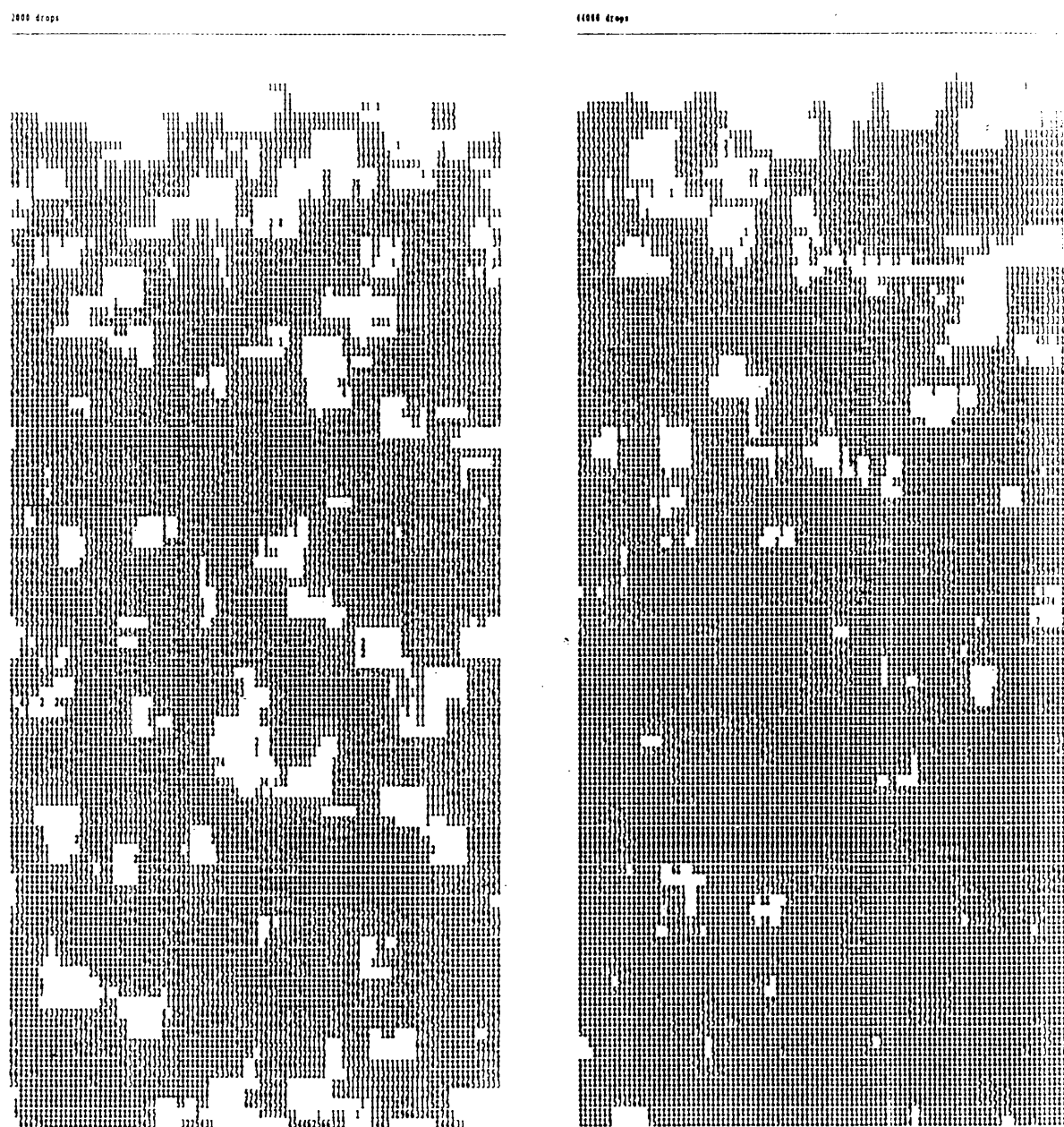


Figure 2.8. Plan view of the contribution of pre-detached particles to RIFT produced after 2000 drop impacts and 44000 drop impacts on a 100 mm by 240 mm cohesive surface by the simulation in Appendix I. Z represents 100%, blank represents <5%, 1,2,...,9 represent 10%,20%,...,90%

FIG. 2.8

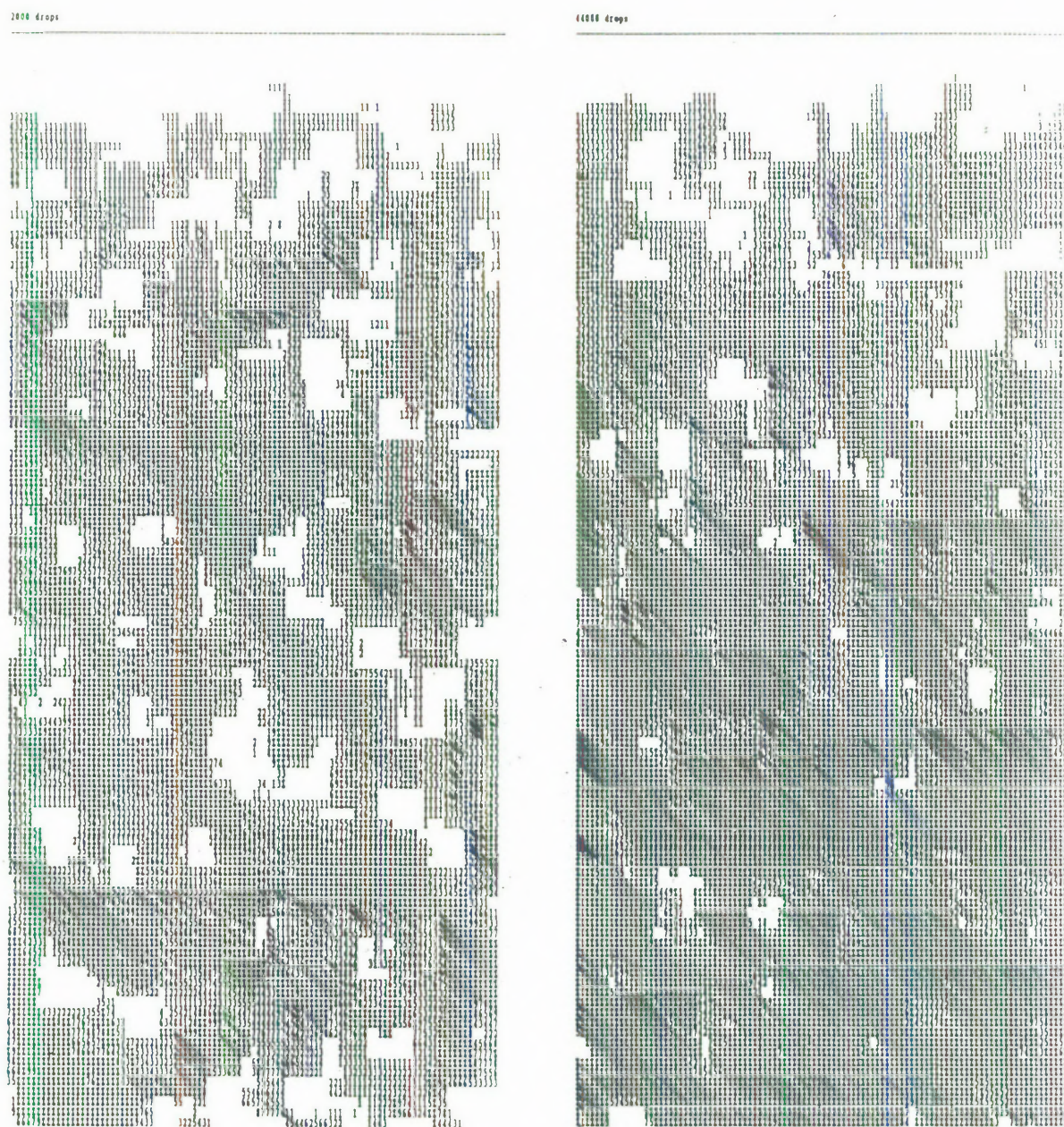


Figure 2.8. Plan view of the contribution of pre-detached particles to RIFT produced after 2000 drop impacts and 44000 drop impacts on a 100 mm by 240 mm cohesive surface by the simulation in Appendix I. Z represents 100%, blank represents <5%, 1,2,...,9 represent 10%,20%,...,90%

FIG. 2.9

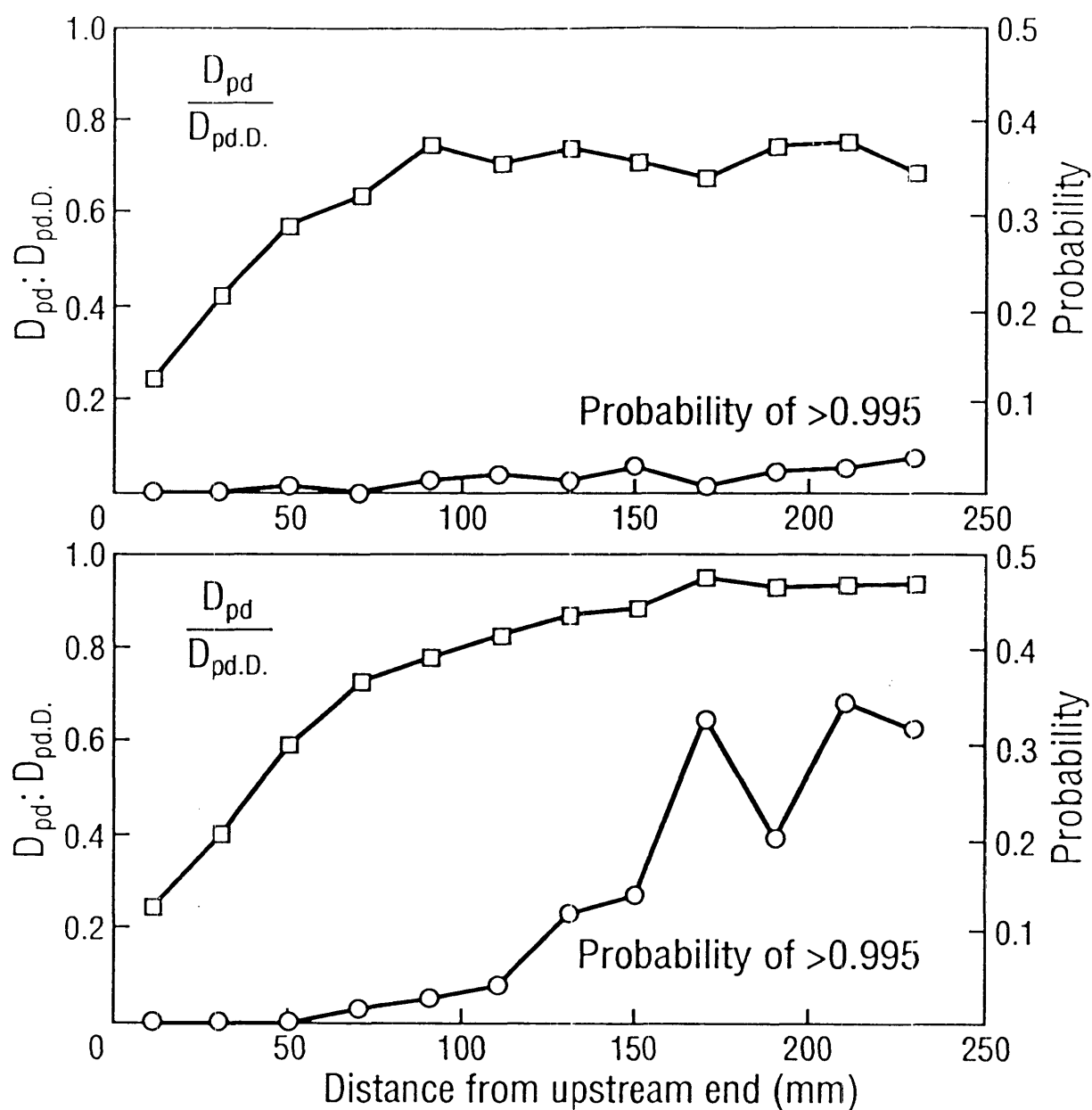


Figure 2.9. Mean D_{pd} to $D_{pd,D}$ ratios (squares) and probabilities of exceeding 0.995 $D_{pd,D}$ (circles) for 20 mm segments during 2000 drop impacts and 72000 drop impacts on a 100 mm by 240 mm cohesive surface in the simulation in Appendix I. The model produces a mean of about 0.94 for the ratio in the downstream segments after the 72000 impacts when $D_{pd,C}=0.2D_{pd,D}$. This increases to 0.98 when $D_{pd,C}=0.6D_{pd,D}$.

drop impacts despite the average depth of the deposit in this zone being sufficient for $H=1$. This is because the detached material is not distributed uniformly across the surface of any element. The random nature of drop impact results in pockets of deposited material developing on the surface because, once a deposit occurs, there is high probability of adding to it before a subsequent impact can move the deposit downstream. Also, if these pockets contain more than sufficient material to protect the underlying surface, drops impacting these zones can only produce $D_{pd} = D_{pd,D}$. Consequently, once developed, these pockets tend to be maintained. As a result of the uneven development of the deposited layer, the condition $H=1$ for the elements at the downstream end of an eroding area is approached asymptotically even though the amount of material deposited in this area is sufficient to completely protect the underlying layer. Overall, the inherent need to store sediment on the surface between drop impacts results in the non-cohesive layer dominating the rate of sediment transport in systems where RIFT is sustained over reasonably long periods.

2.4.2 The influences of x'_{pd} and the $D_{pd,D}:D_{pd,M}$ ratio on H

The effective average distance (x'_{pd}) a particle of size p travels after being lifted from the bed by a drop of size d , has a major influence on H when dynamic equilibrium conditions are reached. If, for example, there is no flow so that $x'_{pd}=0$, then H must be equal to 1 at dynamic equilibrium if there is no other mechanism to transport the particles lifted from the surface (e.g., no splash transport). 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 length of the eroding surface. If these particles are the least transportable of the particles yielded to the flow by the drop impact, then H must be zero at dynamic equilibrium. If these particles are not the least transportable ones, then H lies between 0 and 1 and the effective value of H will vary with the size distribution of the particles being transported. Consider, as a simple example, the situation where clay is mixed with 0.2 mm sand in the case considered in Fig. 2.9. For the 0.2 mm sand, $x'_{pd}=12$ mm and $H=0.93$ at dynamic equilibrium. For clay, x'_{pd} is very large and the effective value of H results from integrating the protective effect of the deposited layer over the whole target. Thus, for the clay, $H=0.64$ at dynamic

equilibrium. Since x'_{pd} is influenced by both particle characteristics and flow velocity (Section 2.3), H at dynamic equilibrium will vary between soils and, as illustrated in Fig. 2.10A, with flow velocity.

For any arbitrary element on the soil surface, the value of H for that element increases with the rate particles are being deposited on the soil surface within that element and decreases with the ability of the drop impacts to remove deposited particles from the surface within that element. If the length of the element is fixed to a value less than x'_{pd} , then not all the particles arriving at the upstream boundary of the element deposit within the element. Some are deposited downstream of the element. Because increases in x'_{pd} increase the area over which particles arriving at the upstream boundary are spread when they are deposited, increases in x'_{pd} decrease the rate of deposition within an element without changing the potential rate of removal from that element. Thus increases in flow velocity and reductions in particle size reduce H . The rate of arrival of material at the upstream boundary depends on the ability of the drops impacting upstream of the element to detach particles from the soil surface. The mass of material detached from the soil matrix by a drop impact when no pre-detached particles are present ($D_{pd.M}$) initially controls the rate material is passed from one element to the next, and subsequently controls the rate material passes out of the most upstream element. Consequently, H decreases with the ratio of $D_{pd.D}$ to $D_{pd.M}$ (Fig. 2.10B).

2.4.3 The influence of entrainment on RIFT

Figure 2.11 shows the extents (x'_{pd}) of 3 different active zones that operate at 3 different flow velocities. From the theory developed in Section 2.4,

$$q_{SR}(p,d) = F_d x'_{pd} D_{pd} \quad (2.25)$$

where, as defined previously, F_d is the spatially averaged drop impact frequency, and D_{pd} is the mass of the p sized particles lifted into the flow by each impact of a d size drop. Since x'_{pd} is linearly dependent on flow velocity (u), it follows from Eq. 2.25 that q_{SR} increases linearly with u .

FIG. 2.10

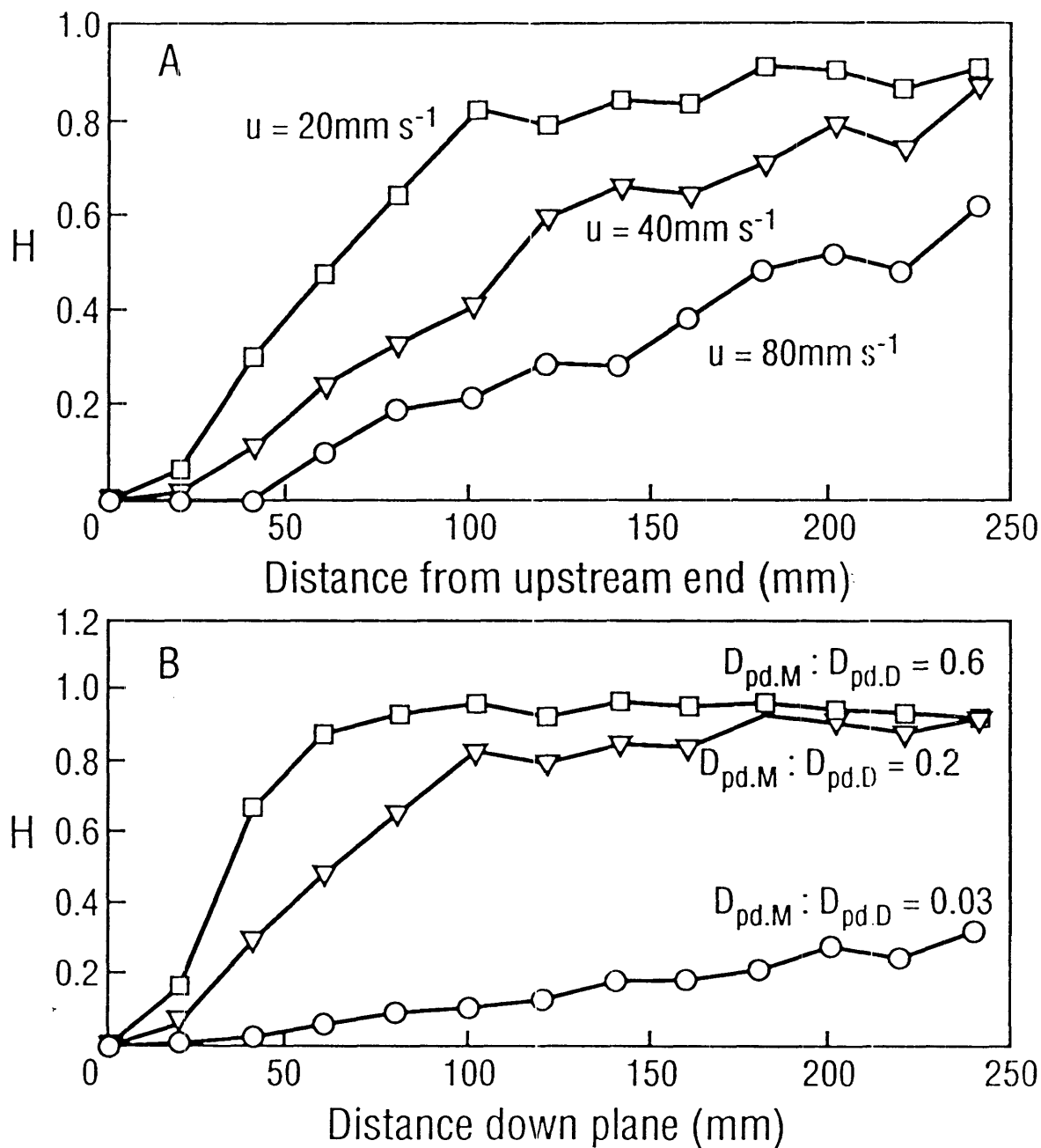


Figure 2.10. The effect of (A) flow velocity and (B) the ratio of $D_{pd.D}$ to $D_{pd.M}$ on H produced after 72,000 drop impacts by the model described in Appendix I.

FIG. 2.11

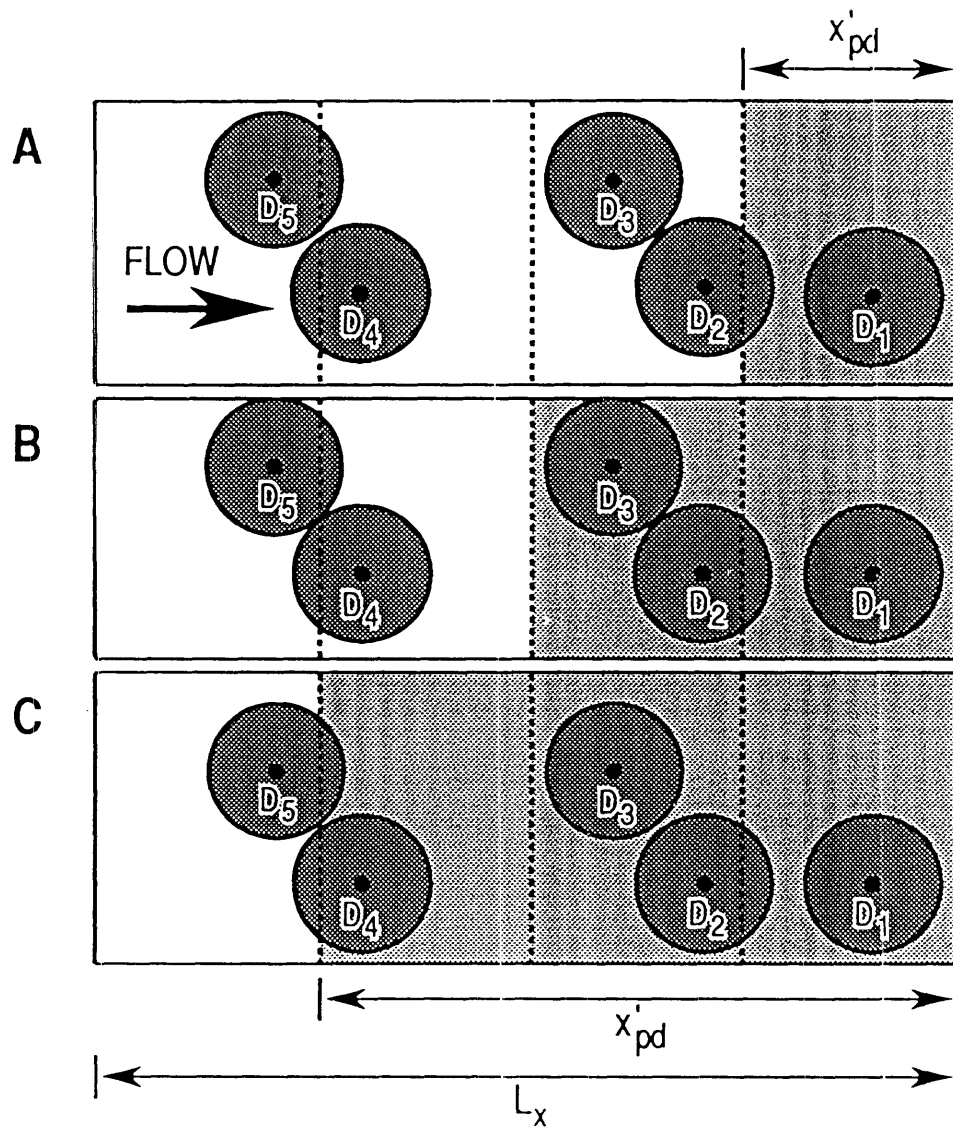


Figure 2.11. Plan view of active zones operating at 3 different flow velocities.

Now consider the situation when $x'_{pd} > L_x$, the length of the eroding surface. No impacts upstream of the distance L_x from the downstream boundary contribute to the discharge of sediment across that downstream boundary so that, once $x'_{pd} = L_x$, all drop impacts upstream of the boundary contribute to q_{SR} and any further increase in u will, as indicated in Fig. 2.12A, not increase q_{SR} . When entrainment occurs, particles move to and across the downstream boundary independently of subsequent downstream drop impacts. This movement is indicated by the dashed line in Fig. 2.13A. If entrainment commences at the top edge of the eroding surface, particles lifted into the flow by the all the drops impacting on the plane are transported without any further aid from raindrop impact if the capacity of the flow to transport entrained material is not exceeded. Effectively, under these circumstances, x'_p goes from a value less than L_x to one greater than L_x once entrainment begins. Thus q_{SR} will jump in value when the critical velocity for entrainment is reached but then, as indicated in Fig. 2.12B, increase no further as flow velocity increases. However, q_{SR} increases with distance in the downstream direction and the mass of particles lifted into the flow by the drop impacts may, at some point on the plane, reach a level which exceeds the capacity of the flow to entrain particles. Particles lifted into the flow by drops impacting downstream of this point travel a "finite" distance as indicated by the solid line in Fig. 2.13A. As a result of this, and the influence of flow velocity on the capacity of the flow to entrain particles, q_{SR} increases with flow velocity (Fig. 2.12B) if the entrainment capacity is satisfied on the plane. The rate that material is presented to the flow for entrainment also varies with drop impact frequency and consequently, a change in the slope in the relationship between q_{SR} and drop impact frequency occurs when the impact frequency is sufficient to cause the entrainment capacity to be satisfied on the plane (Fig. 2.13).

2.4.4 Concluding Discussion

There is a need to consider the effect of the deposited layer in many field and laboratory situations. For example, Fig. 2.14 shows data collected from 2 rainfall events (assuming that rainfall events are separated by 30 mins or more) that occurred on one day on a 40 m long, 2.7 m wide non-vegetated runoff and soil loss plot with a slope gradient of 4.2 % in experiments reported by Kinnell (1983). The soil used in these experiments was a yellow

FIG. 2.12

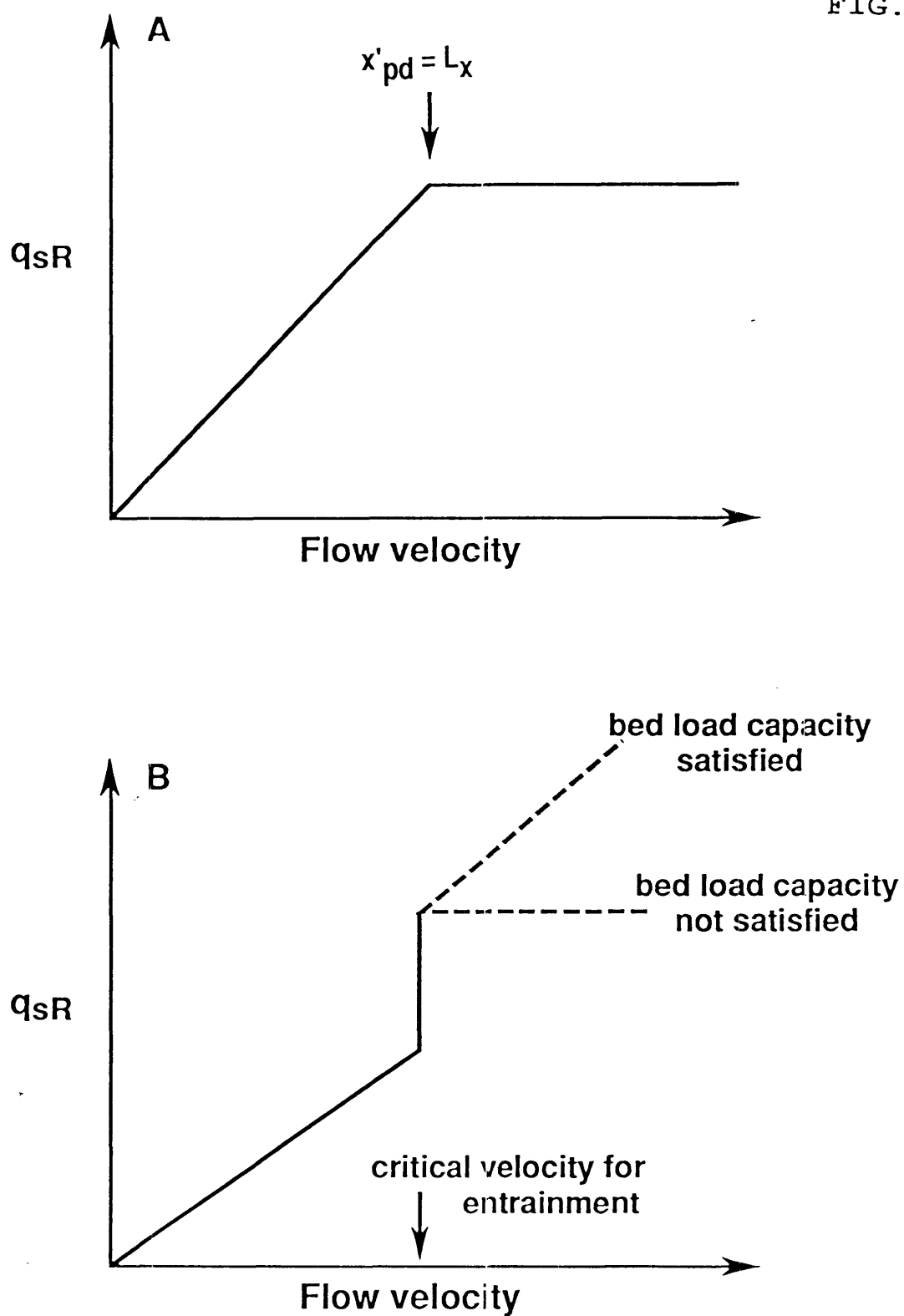


Figure 2.12. Response of q_{sR} to flow velocity (A) when entrainment does not occur and (B) when entrainment occurs on an eroding surface.

FIG. 2.13

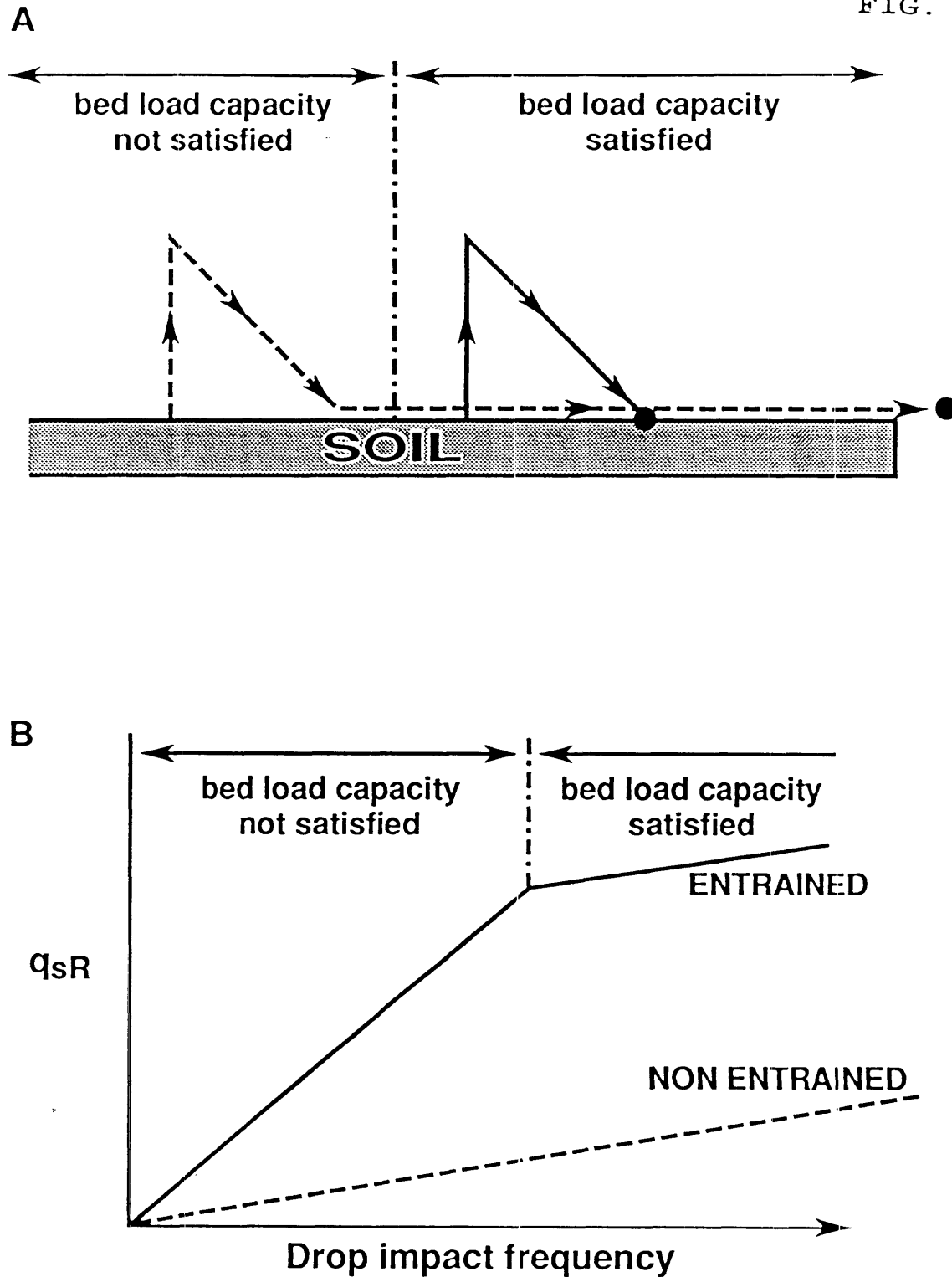


Figure 2.13. Schematic representations of the effect bed load capacity becoming saturated on (A) particle travel on an eroding surface, and (B) the relationship between q_{sR} and drop impact frequency.

FIG. 2.14

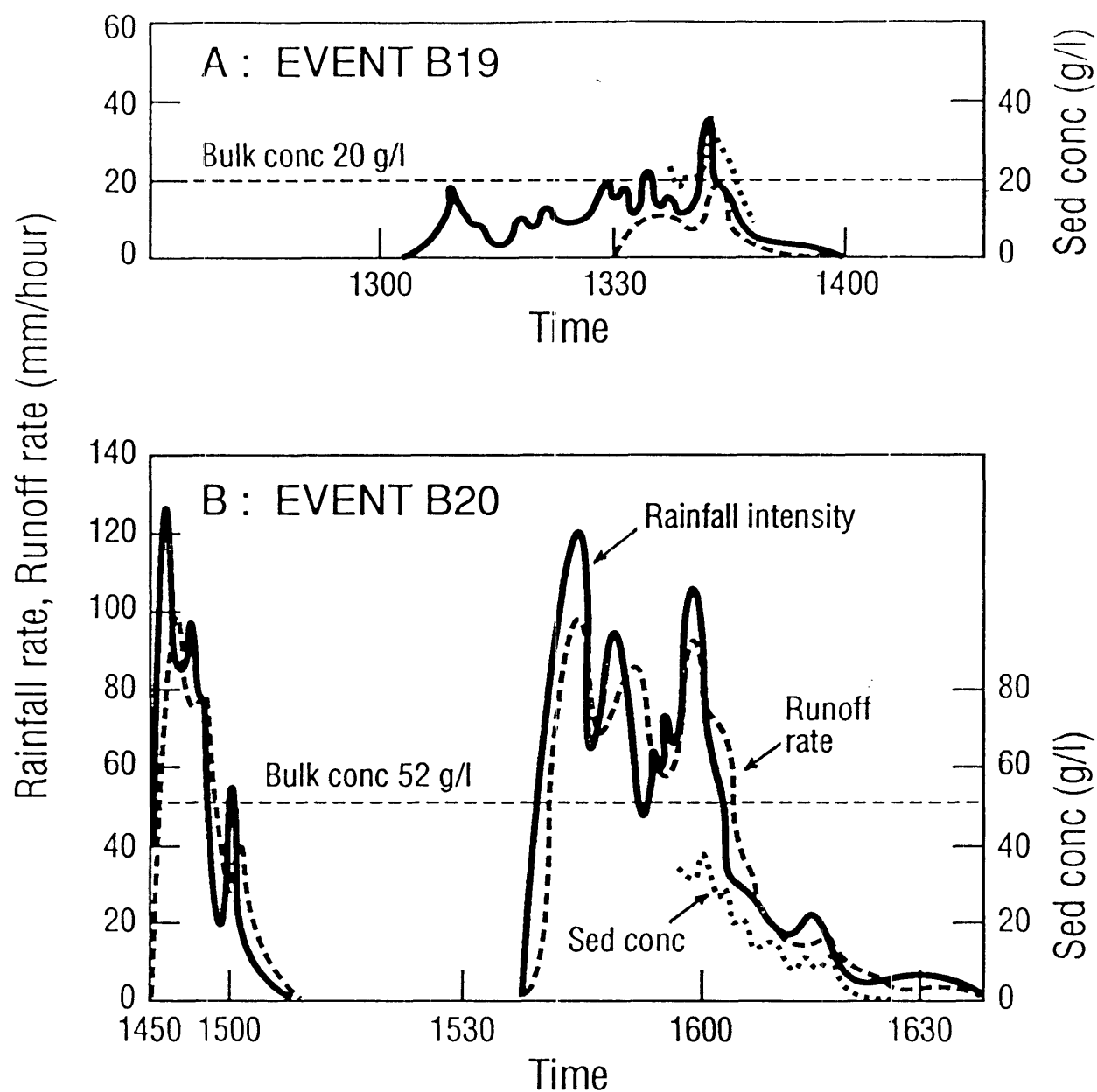


Figure 2.14. Rainfall, runoff and sediment concentrations measured during two rainfall events in experiments with bare runoff and soil loss plots reported by Kinnell (1983).

podzolic (Stace et al., 1968), or, in the US Soil Taxonomy (Soil Survey Staff, 1975), 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 in the plot most of the time. 18 rainfall events occurred between the time the plot was cultivated and the events shown in Fig. 2.14. During event 19, a considerable amount of pre-detached material lay on the surface as the result of raindrop impact prior to and during the event and the peak in erosive stress that occurred at towards the end of the event resulted in an above average sediment concentration. However, during event 20, the pre-detached material was flushed from the surface so that a period of high erosive stress the occurred towards then end of this event produced lower than average sediment concentrations. During event 19, the susceptibility of the soil to erosion was dominated by $D_{pd,D}$ where as $D_{pd,M}$ was dominant in event 20 particularly during the period when the sediment concentrations were measured.

The results produced by the model used here illustrate the dynamic nature of the deposited layer and how, in a qualitative way, various factors influence it and how it influences the erosion rate. It follows from the results presented here that the protective effect of the layer of pre-detached particles is complex and involves not only those particles that are being transported but also those that are not. Obviously, variations in particle characteristics, such as particle size and density, and rainfall characteristics, such as drop size and velocity, must influence the development of the layer and its effect on erosion. The enormity of the task of keeping track of the effect of individual drop impacts over large areas makes the use of modelling concepts described here impractical for field sized areas. However, an alternative procedure will be suggested later (Chapter 5).