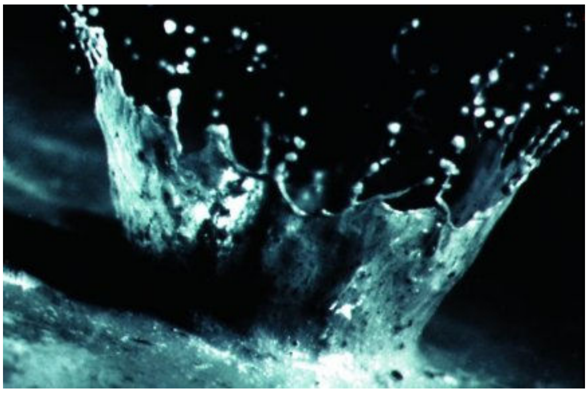
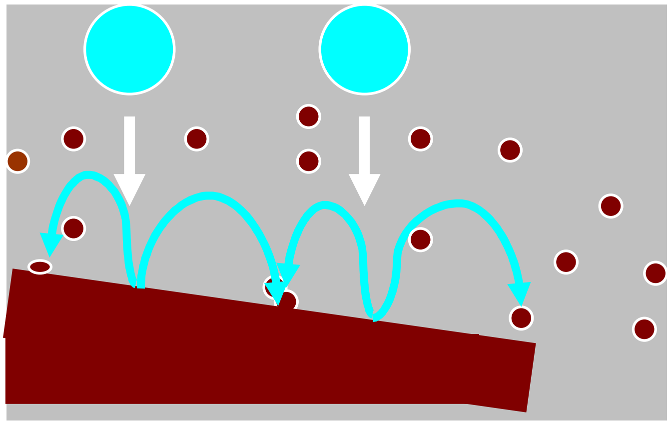
Interrill and Sheet Erosion

Erosion involves the detachment (the plucking) of particles held within the soil surface by cohesion and inter-particle friction and the subsequent transport of the detached material away from the site of detachment. Interrill and Sheet Erosion are both dominated by the same detachment and transport mechanisms. In Interrill and Sheet Erosion, the primary agent causing detachment is raindrop impact. Raindrops, particularly large ones, can have sufficient energy to overcome the cohesive and inter-particle friction forces holding particles in the soil surface.

Splash Erosion

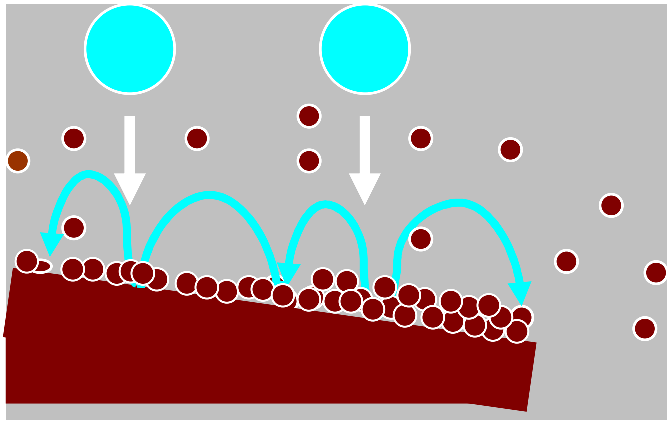


When the surface is dry, or a very thin film of water exists on the surface, drops impacting the surface produce splash that can transport particles away from the site of detachment. On flat surfaces, splash tends to travel equally in all directions so that material splashed from one point is replaced by material splashed to that point from drops impacting in the surrounding area. While considerable amounts of soil may be detached in these circumstances, the net loss from a location is negligible. Consequently, the area does not in fact erode but the drop impacts play a major role in modifying the characteristics of the soil surface. Surface roughness is reduced and particle breakdown can occur resulting in the surface becoming crusted. However, if there is a slope gradient, more of the detached material will be transported in the down slope direction than the upslope direction and a net loss of soil material from the area occurs.



Consequently, the ability of splash erosion, the term given to the combination of detachment by drop impact and transport by drop splash, to cause erosion increases as the gradient of the area increases.

Splash transport limits splash erosion because it is not an efficient transport system. Initially, the rate at which material detached exceeds the rate at which is transported and this leads to a layer of loose particles sitting on top the cohesive soil surface.



Those loose particles require energy to move and so, when they are present, loose particles reduce the energy available to cause detachment. Eventually, on a flat surface, the depth of loose material will reach the point where drop impacts fail to penetrate and detach particles from the underlying cohesive soil surface. If H_S is the degree of protection provided by the layer of loose material, and H_S has a value of 1.0 when loose particles fully protect the cohesive soil surface, then

$$M_{DSd} = M_{DSd.0}\,(1 - H_S) \qquad (1)$$

where M_{DSd} is the mass of material detached and splashed by drops of size d, $M_{DSd.0}$ is the mass detached and splashed when there are no loose particles on the cohesive soil surface and H_R has a value of 0. When $H_S = 1.0$, all the material splashed comes from the layer of loose particles. The mass of material splashed from the layer of loose particles by a drop of size d (M_{LSd}) varies with H_S, being at a maximum when $H_S = 1.0$ and zero when $H_S = 0$. Thus

$$M_{LSd} = M_{LSd.1}\,H_S \qquad (2)$$

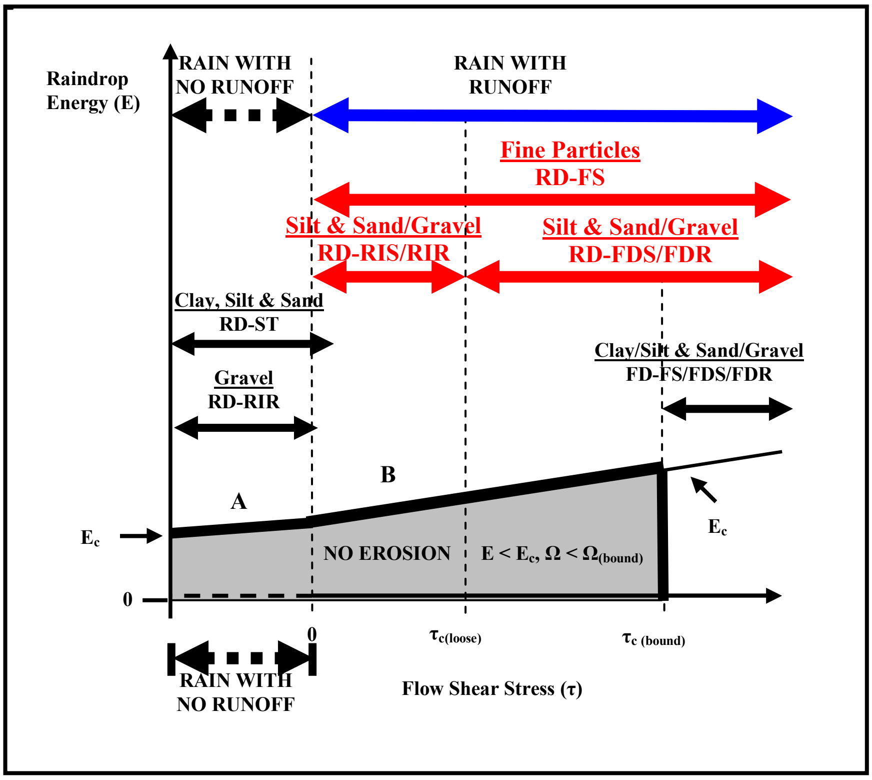
where $M_{Ld.1}$ is the mass splashed when $H_S = 1.0$. Consequently, the total mass splashed by a drop of size d is given by

$$M_{Sd} = M_{DSd} + M_{LSd} = M_{DSd.0}\,(1 - H_S) + M_{LSd.1}\,H_S \qquad (3)$$

M_{DSd} is influenced by moisture content of the surface when water is not present on the surface. Because the loose particles are held on the surface by only gravity, M_{LSd} is greater than M_{DSd}. On sloping areas where particles are being splashed down slope, H_S increases in the downslope direction. The absorption of drop energy in a layer of water sitting on the surface reduces both M_{DSd} and $M_{LSd.}$

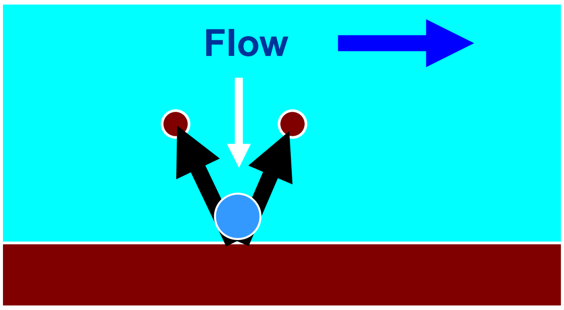
Erosion by Rain Impacted Flow

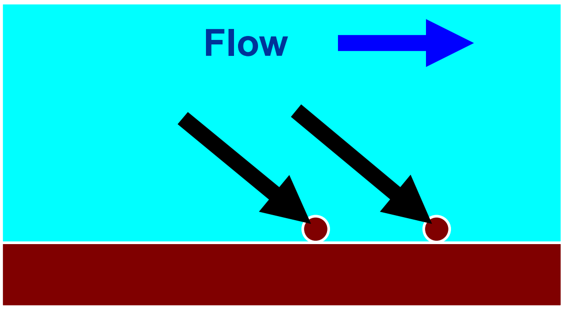
The trajectories of splash vary with water depth and so water depth influences the distance particles are splashed. This influences the efficiency of splash transport. Ultimately, increases in water depth cause splash to become insignificant as an agent transporting soil particles downslope. However, particles can still be detached and loose particles lifted into flowing water resulting in transport occurring within the flow. In flowing water, particles detached by raindrop impact (RD) may move downstream by remaining in suspension (FS) or by raindrop induced saltation (RIS), or by raindrop induced rolling (RIR), or by flow driven saltation (FDS) or by flow driven rolling (FDR) depending on the size and density of the particles and the flow conditions as indicated in the figure below.



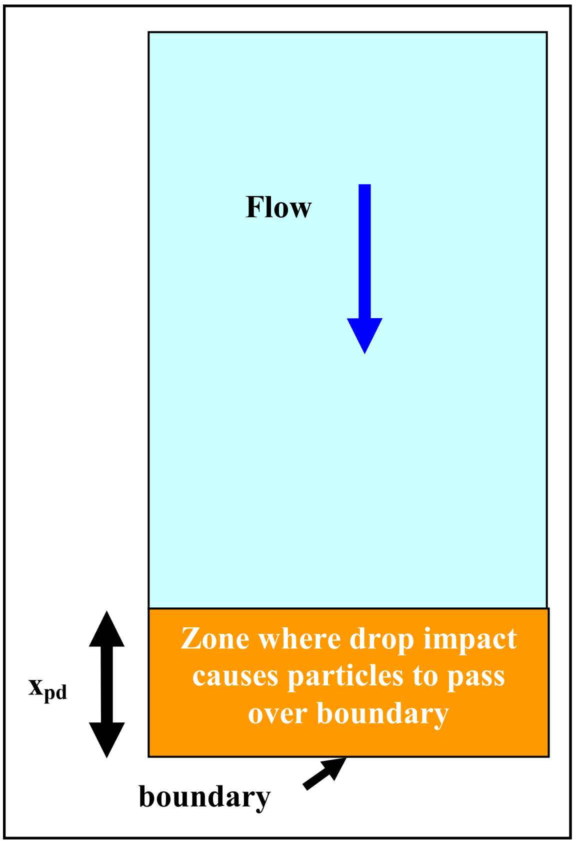
In rainfall erosion both raindrop impact and surface water flows can cause detachment. Flow detachment (FD) only occurs when the flow shear stress is greater than $\tau_{(bound)}$. Below that value, detachment results from only drop impact. When the shear stress is greater than $\tau_{(loose)}$, particles detached by raindrop impact move down stream by flow driven saltation (FDS) or rolling (FDR). When the shear stress is less than $\tau_{(loose)}$, while fine detached particles move downstream by remaining suspended in the flow (FS), those that fall back to the surface move only when stimulated to do so by drop impacts through the process called raindrop induced saltation (RIS).

Raindrop induced saltation





When raindrop induced saltation is caused by a drop of size d, particles lifted into the flow fall back to the soil surface as the result of gravity. Because the water is flowing, the particles move down stream during that fall. The distance they move (x_{pd}) depends on the time they remain suspended in the flow (t_{pd}) and the velocity of the flow (u). t_{pd} depends on the height the particles are lifted into the flow, and the size and density of the particles. Only drops impacting in the zone that extends a distance x_{pd} upstream of a boundary will cause particles to pass across that boundary without action from subsequent drop impacts.



As a result, the discharge (mass/width/time) of particles of size p by the impacts of drops of size d (q_{SR}(p,d))is given by

$$q_{SR}(p,d) = M_{Rpd}\, X_{pd}\, F_p \qquad (4)$$

where M_{Rpd} is the mass of particles lifted into flow by drops impacting in that zone that move by raindrop induced saltation, F_p is the frequency (number/area/time) of the impacts of drops of size d in that zone, and X_{pd} is the effective average distance of particle travel associated with those impacts. As with splash erosion, raindrop induced saltation causes detached particles to sit upon the cohesive soil surface while they wait for a subsequent drop impact to induce them to move down stream. As with splash erosion, the presence of loose particles on the surface provides a degree of protection (H_R) against detachment. Consequently, when H_R varies between a maximum of 1.0 and a minimum of zero, the total mass induced to saltate by a drop of size d (M_{Rpd}) is given by

$$M_{Rpd} = M_{DRpd} + M_{LRpd} = M_{DRpd.0}\,(1 - H_R) + M_{LRpd.1}\, H_R \qquad (5)$$

where M_{DRpd} is the mass of material detached and induced to saltate by drops of size d, $M_{DRpd}$is the mass induced to saltate from the loose layer, $M_{DRpd.0}$ is the mass detached and induced to saltate when there are no loose particles on the cohesive soil surface and H_R has a value of 0, and $M_{LRpd.1}$ is the mass induced to saltate by a drop when H_R = 1.0. Conceptually, Eq. 4 can be applied to particles that roll when the average distances the particles roll after a drop impact are known or can be estimated.

The effect of water depth on raindrop induced saltation

The water layer in rain impacted flows absorbs some of the kinetic energy associated with an impacting raindrop. Generally, the deeper the flow the less the energy that is available to cause particle detachment and uplift. As a result, M_{Rpd} decreases as flow depth increases. Also,

$$X_{pd} = T_{pd}\, u \qquad (6)$$

where T_{pd} is the effective average time particles remain in the flow during the saltation episode that follows a drop impact, and flow depth influences T_{pd}. Combining Eqs 4 and 6 gives

$$q_{SR}(p,d) = M_{Rpd}\, X_{pd}\, F_p = M_{Rpd}\, T_{pd}\, u\, F_p \qquad (7)$$

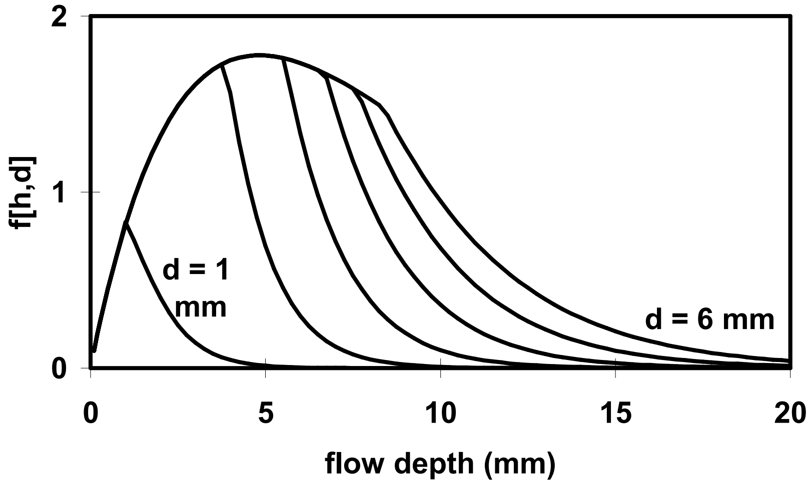
When flow depth (h) = 0, $T_{pd} = 0$ because all detached material is transported by drop splash. As flow depth increases, initially the height particles are lifted into the flow is restricted by the height of the water layer above the surface. This restriction is removed as flow depth increases further but the reduction in raindrop energy available for detachment and uplift leads to T_{pd} becoming maximised at a drop size dependent flow depth before decreasing as flow depth increases further. This, coupled with the decline in M_{Rpd} with flow depth results in $q_{SR}(p,d)$ reaching a maximum value at a drop size dependent flow depth. Experiments with rain impacted flows over non-cohesive surfaces where $M_{Rpd} = M_{LRpd}$ have established that

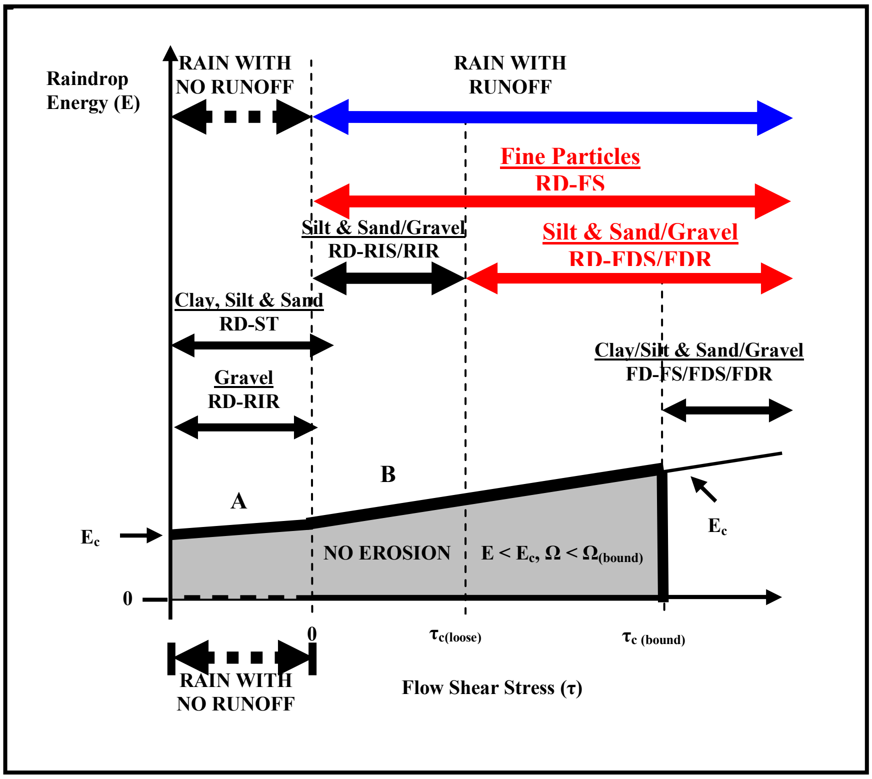
$$q_{SR}(p,d) = a_p\, u\, I_d\, f[h,d] \qquad (8)$$

where a_p is a factor that is dependent on particle size and density, I_d is the intensity of rain made up of drop of size d, and f[h,d] is a flow depth related function which takes account of the variations in product of M_{Rpd} and T_{pd}. The restriction placed on the height particles are lifted in the flow by the height of the water surface when flow depths are low results in the product of M_{LRpd} and T_{pd} becoming insensitive to drop size variations when flow depths are low. The variation in f[h,d] with flow depth and drop size is represented mathematically by

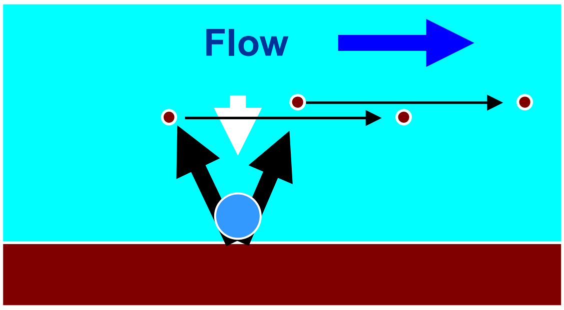
$$f[h,d] = h \exp(-0.207\, h) \qquad , h < h_{cd} \qquad (9a)$$
$$f[h,d] - h \exp(-0.207\, h - b_d\, (h - h_{cd})) \qquad , h \geq h_{cd} \qquad (9b)$$

where h is in millimetres, b_d and h_{cd} are drop size dependent factors, and is shown graphically by



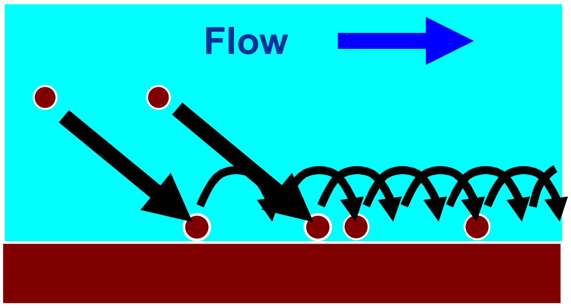


Fine particles travelling in suspension



Fine particles that remain suspended in the flow after a droop impact move down stream without any further action from raindrop impacts. In terms of Eq. 4, X_{pd} for these particles is the distance from the point of detachment to the point where the flow is discharged. Because these particles do not settle back to the bed, $M_{LRpd} = 0$ for these fine particles.

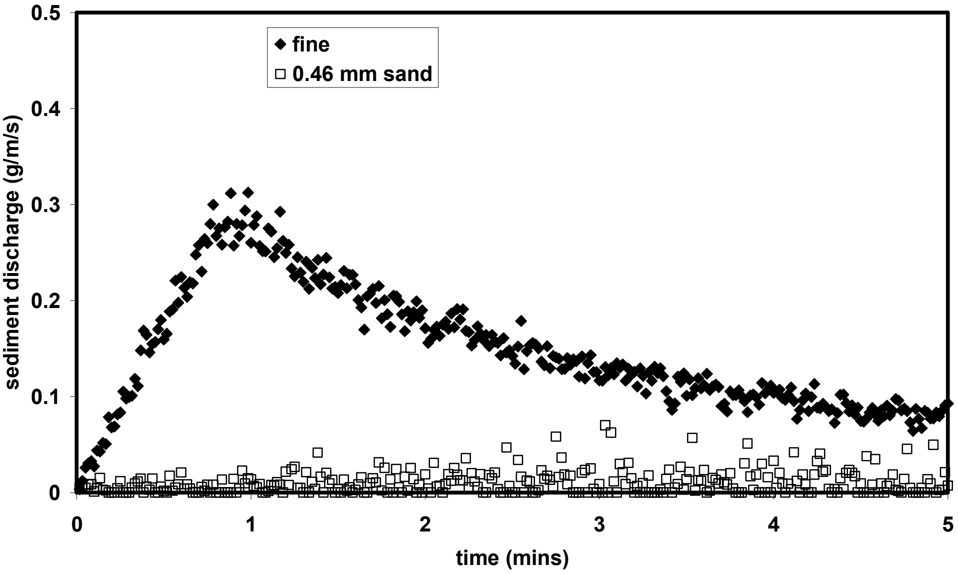
Flow driven saltation



Raindrop induced saltation occurs when the flow shear stress is below $\tau_{(loose)}$. When raindrop impact lifts soil particles up into the flow where the flow shear stress is greater than $\tau_{(loose)}$, particles lifted into the flow by drop impact move downstream by flow driven saltation. As with fine particles travelling in suspension, X_{pd} for these particles is the distance from the point of detachment to the point where the flow is discharged and $M_{LRpd} = 0$. $\tau_{(loose)}$ varies with particle size and density, being higher for larger heavier particles than smaller lighter particles.

Particle travel rates and sediment composition

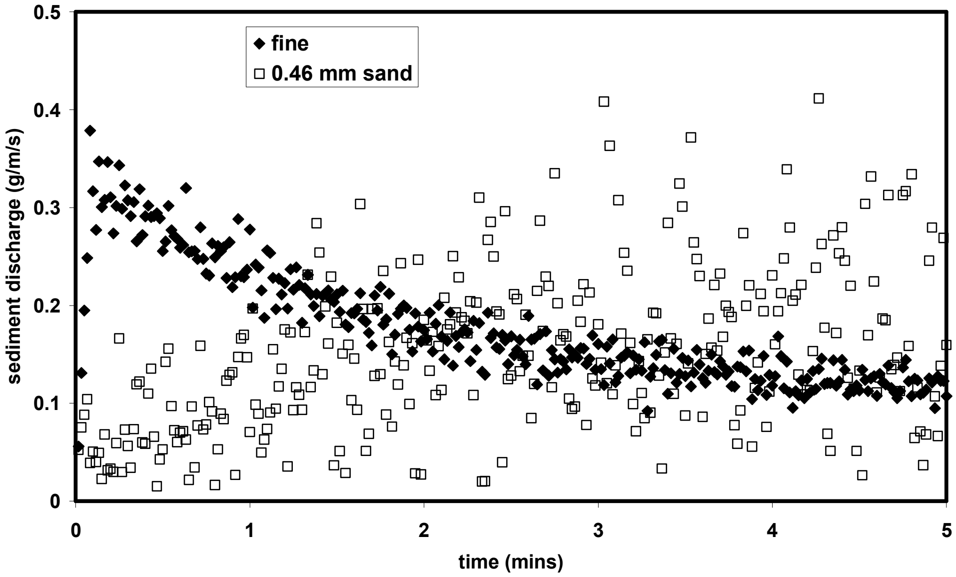
Particles detached from the soil surface move downstream at different rates depending on their mode of transport. Particles that remain suspended in the flow travel at the velocity of the flow. Particles travelling by saltation travel at lower velocities because they spend some time on the bed between saltation jumps. With flow driven saltation, the downstream velocities are controlled entirely by the energetics of the flow. The raindrop induced saltation, drop impact frequency also has an effect, and the size and density of the particles influences the distance the particles travel during the saltation jumps. As a result, the rates particles of various sizes and densities travel across the surface by raindrop driven saltation depends on their size and density. Also, there are interaction effects. For example, as indicated by Eq. 7, the layer of loose particles sitting on the surface associated with transport by raindrop induced saltation influences that ability of impacting raindrops to cause detachment. If initially there is no loose material, then detachment over the whole eroding area is simply controlled by flow depth and drop size. However, as the particles move downstream by raindrop induced saltation, detachment is reduced as time progresses. This results in the amount of fine material that remains suspended in the flow (RD – FS) initially increasing but then decreasing with time.



The above figure shows sediment discharges of fine particles travelling in suspension and sand particles travelling by raindrop induced saltation on a 0.25 m wide by 0.5 m long surface covered by a 7 mm deep flow with a velocity of 10 mm/s when impacted by 2.7 mm drops giving a rainfall intensity of 60 mm/h produced by mathematical simulation of sediment transport in rain-impacted flow. The scatter is caused by the fact the discharges presented were generated over 1 second intervals and the raindrop impacts occurred randomly in space.

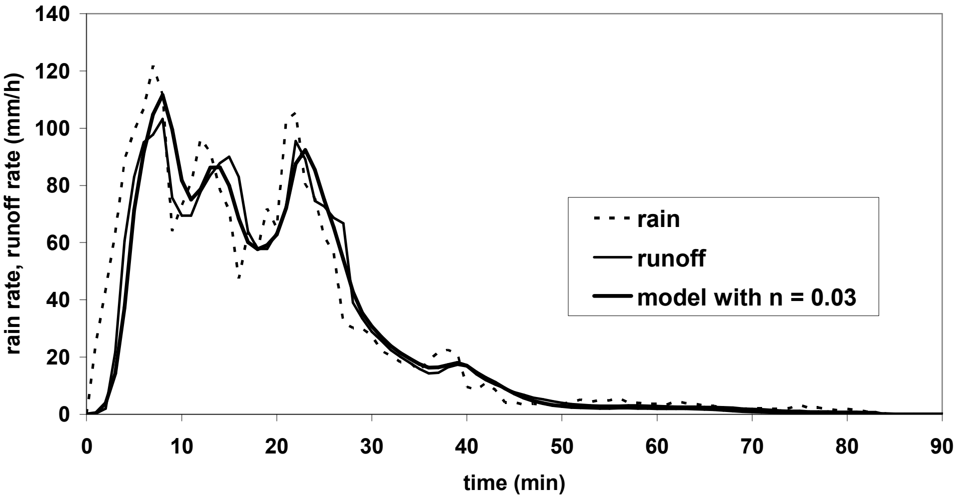
Although the presence of loose material sitting on the bed reduces detachment, increases in H_R cause the discharge of material travelling by raindrop induced saltation to increase because $M_{LRpd.1}$ is greater than $M_{LRpd.0}$. For a given rainfall – runoff situation, an amount of time is required for a particle with any given particle size – density combination to travel from the most distant point of detachment to the point where it is discharged. Once that time has expired, the discharge of particles of that size – density combination reaches a steady state in a simple situation like, where modelled above, the particles moving by raindrop induced saltation are uniform in size and density.

Particles travelling by raindrop induced saltation travel downstream at a rate that varies with X_{pd}, and X_{pd} varies with flow velocity so that the time taken for the loose layer to develop fully decreases with flow velocity. This results in the discharge of the fine material peaking earlier when flow velocities increase.



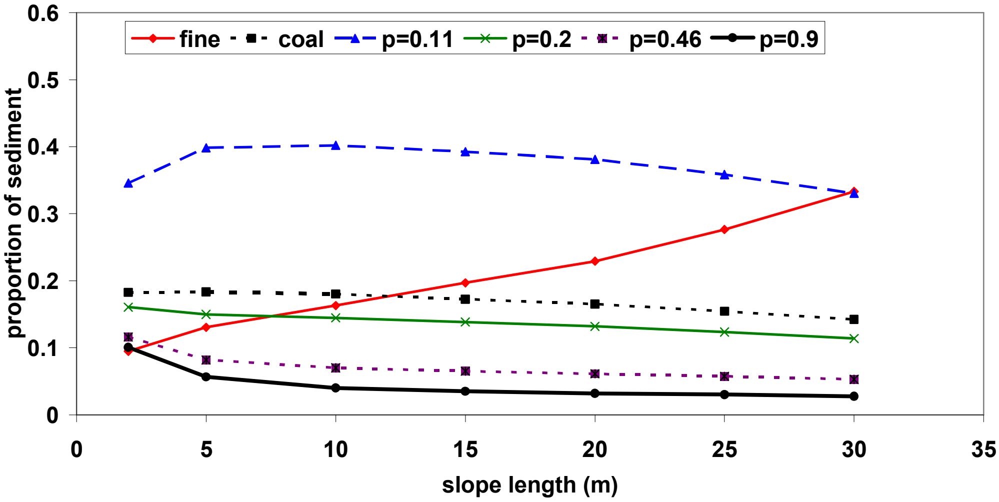
The above figure shows sediment discharges of fine particles travelling in suspension and sand particles travelling by raindrop induced saltation on a 0.25 m wide by 0.5 m long surface covered by a 7 mm deep flow with a velocity of 100 mm/s when impacted by 2.7 mm drops giving a rainfall intensity of 60 mm/h produced by mathematical simulation of sediment transport in rain-impacted flow. The scatter is caused by the fact the discharges presented were generated over 1 second intervals and the raindrop impacts occurred randomly in space.

The depth of the layer of loose particles is dependent on both the rate of detachment and the rate of transport by raindrop induced saltation. The depth tends to decrease as the transport rate increases but, given Eq. 7, the detachment rate increases as the depth of the layer of loose particles decreases. In natural rainfall, rainfall intensity and runoff depths and velocities vary in time and space.



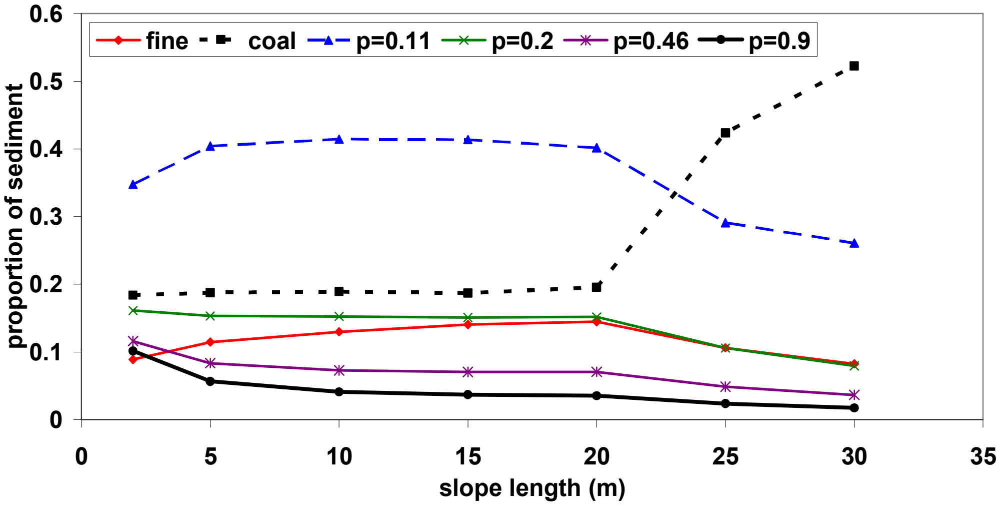
Rainfall and runoff produced by a natural rainfall event on a 40 m long bare fallow plot on a slope gradient of 4 % near Canberra, ACT, Australia.

This, together with the effect of factors like slope length and gradient, leads to relatively complex interactions controlling the composition of the sediment discharged during a rainfall event.



Sediment compositions produced for the rainfall event shown above by mathematical simulation of detachment and transport in rain-impacted flows by 2.7 mm drops on plane bare surfaces of lengths up to 30 m long inclined at 0.5%. The cohesive surface contained equal amounts of coal, 0.11 mm sand, 0.2 mm sand, 0.46 mm sand and 0.9 mm sand

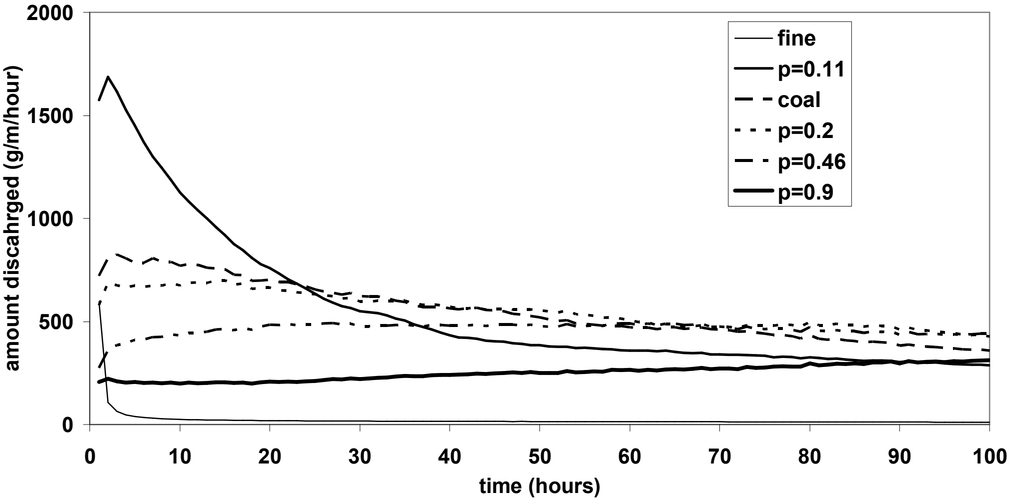
In addition, flow conditions along a line of flow may be such that at some point on the surface, particles moving by raindrop induced saltation may subsequently move by flow driven saltation. The rainfall event being considered produced peak flow velocities that resulted in such a transition to occur on slopes longer than 20 m for a short period of time when the slope gradient was 5 %.



Sediment compositions produced for the rainfall event shown above by mathematical simulation of detachment and transport in rain-impacted flows by 2.7 mm drops on plane bare surfaces of lengths up to 30 m long inclined at 5%. The cohesive surface contained equal amounts of coal, 0.11 mm sand, 0.2 mm sand, 0.46 mm sand and 0.9 mm sand.

Because flow driven saltation is more efficient in transporting detached material than raindrop induced saltation, as shown above, the temporary change in the transport mode enhanced the presence of coal in the sediment discharged by the event.

In the majority of rainfall erosion experiments little regard is given to determining the composition of the sediment discharged or the fact that different soils may behave differently to particular combinations of rain and flow conditions. When rain is applied to an inclined surface, it takes time for the water to flow from the top to the bottom. When the rainfall intensity remains constant, the rate water is discharged from the bottom of that surface increases until water from the very top of the surface reaches the bottom. The rate then becomes steady. The time taken to reach the steady is the time of concentration. Often in rainfall simulator experiments designed to paramaterize erosion models, sediment discharge data collected once runoff rate stabalizes is used. However, the time for particles detached at a certain point on an eroding area to travel to the point where they are discharged is, in many cases, very much longer than for water to flow from that point.



Discharges of fine and sand size particles transported by suspension and raindrop induced saltation produced by 2. 7 mm drops with a constant 50 mm/h intensity rain on a 10 m bare long plot with a 9 % slope. The cohesive surface contained equal amounts of coal, 0.11 mm sand, 0.2 mm sand, 0.46 mm sand and 0.9 mm sand.

Times of concentration exist for each particle size – density combination being transported in rain-impacted flow, and the particle size distribution of the sediment discharge will not stabalize unless all the times of concentration are have been exceeded. The times of concentration vary with flow velocity. Ignoring the effect of the different particle travel rates may lead to incorrect model outcomes.

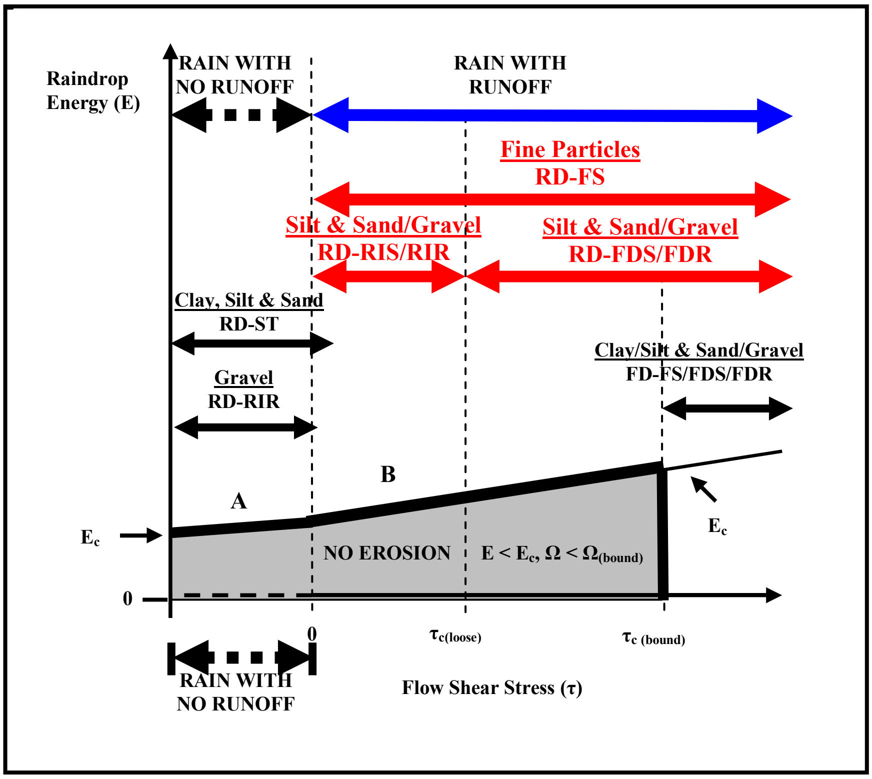
In addition to failure to consider how particle travel rates influence the interpretation of the results from rainfall erosion experiments, the effect of changes in detachment and transport processes can lead to prediction errors with certain models. For example, in the WEPP interrill erosion model

$$D_i = K_i \, I \, q \, S_f \tag{10}$$

where D_i is the mass per unit area discharged from the interrill area, K_i is the interrill soil erodibility factor, q is the runoff rate (volume/area) and S_f is the slope gradient factor given by

$$S_f = 1.05 - 0.85 \exp(-4 \sin(\theta)) \tag{11}$$

where θ is the angle of the slope to the horizontal. However, there are experiments (eg. see Kinnell, P.I.A, and Cummings, D. 1993. Transactions of the American Society of Agricultural Engineers 36; 318-387) where the effect of slope gradient on D_i differed markedly from Eq. 11.



Micro rilling can occur in interrill areas as $\tau_{(bound)}$ is exceeded as slope gradient increases and sandy soils are more at risk than most clayey soils. $\tau_{(loose)}$ values vary between soils so that the mix of transport systems may vary considerably between soils as slope gradients vary.

Conceptually, rain has a certain power to cause erosion (erosivity) while soil surfaces have a certain susceptibility to erosion (erodibility). While those concepts have formed the basis of many rainfall erosion models that have been developed in the past, they fail to recognise that the detachment and transport processes involved in rain-impacted flows do not always operate in the same way as rainfall and runoff conditions vary on different soils. The fact that particles with different particle size – density combinations travel downstream at different rates so that their times of concentration vary from that of the flow to near zero raises issues about the interpretation of results from rainfall erosion experiments.

- How usefully are the results given the rainfall – runoff conditions involved ?
- How long should a rainfall simulation experiments be run before data for parameterising erosion prediction models should be collected ?

Literature

Many of the figures shown here can be found in one or more of the following papers

- Kinnell, P.I.A. Earth Surface Processes and Landforms 26;749-758 (2001)
- Kinnell, P.I.A. Hydrological Processes 10; 2815-2844 (2005)
- Kinnell, P.I.A. Catena 78; 2-11 (2009)
- Kinnell, P. I.A. (www.interscience.com) DOI: 10.1002/esp.1828