Comment on 'A physical model of particulate wash-off from rough impervious surfaces' by Shaw et al. [Journal of Hydrology 327 (2006) 618–626]

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Received 14 September 2007; accepted 8 December 2007

Shaw et al. (2006) presented data from experiments using a small flume (10.5 × 80 cm) with rain-impacted flow where rainfall intensity and upslope overland flow were controlled independently. The experiments involved placing various masses of 500–590 µm sand in a 10 cm long source zone, the top of which was nearly half way down the 80 cm long flume. Rainfall was applied by 4 hypodermic needles that oscillated along two orthogonal tracks 3 m above the flume. A full cycle up and down the flume was completed every 22 s. Shaw et al. concluded that, for initial spatial densities greater than about 0.036 g cm⁻² in the source zone, the rate of increase in the peak rate of the loss of sand from the flume was constrained over the range of inflows (305–565 mL min⁻¹) and rainfall rates (0.07–0.13 cm min⁻¹) used in their experiments. As a result, Shaw et al. developed a finite difference model based on the approach developed by Hairsine and Rose (1991) which yielded

\[ \frac{\partial M_g}{\partial t} = h - e \]  

(1)

where \( h \) is the settling rate (g cm⁻² min⁻¹) of the mass of ejected particles, and

\[ e = aP M_g, \quad M_g < M_0 \]

\[ e = aP M_0, \quad M_g \geq M_0 \]  

(2)

where \( e \) is the raindrop-induced ejection rate (g cm⁻² min⁻¹), \( a \) is an experimentally determined "detachability" constant that accounts for the mass loss per drop, \( P \) is rainfall intensity (cm min⁻¹), \( M_g \) is the mass of the particles per unit area on the surface (g cm⁻²), and \( M_0 \) is the spatial density of material on the surface at which particles no longer move without measurable interaction with other particles. Eq. (2) was based on a transport model describing the movement of non-interacting particles

\[ e = aP M_g \]  

(3)

derived from a stochastic sediment transport model developed Lisle et al. (1998). Once lifted into the flow, sand particles return to the bed under the influence of gravity. Energy is absorbed in lifting loose material up into the flow and, as a consequence of this, there is a certain spatial density of the loose material on the bed where the depth of the material is sufficient to protect particles below that depth from being lifted into the flow. Shaw et al. concluded that the constraint on the rate of mass loss when \( M_g > M_0 \) was the result of surface particles shielding underlaying particles from the effect of rain drops.

Although Shaw et al. report that their model produced results that agreed well (\( r^2 > 0.85 \)) with the data obtained...
from their experiments, Kinnell (2006) developed a mechanistic simulation model to illustrate how sand particles moving by raindrop impact stimulated saltation and fine particles moving in suspension interact in controlling the discharge of sediment from cohesive surfaces. As reported below, this model was adapted to examine the situation where various amounts of 0.46 mm sand were placed in a 100 mm long zone upstream of a 300 mm long non-eroding surface covered by a 7 mm deep flow moving at 100 mm s⁻¹ impacted by 2.7 mm drops with a rainfall intensity of 60 mm h⁻¹.

When sediment transported by raindrop impact stimulated saltation is discharged across any arbitrary boundary, \( q_{sr}(p,d) = M_{pd} F_{d} X_{pd} \) (4)

where \( q_{sr}(p,d) \) is the mass material of size \( p \) discharged per unit width of flow in unit time in association with the impact of raindrops of size \( d \), \( X_{pd} \) is the effective average distance particles of size \( p \) travel after being lifted into the flow by the impact of drops of size \( d \), \( M_{pd} \) is the mass of particles lifted up into the flow by drops of size \( d \) impacting within a distance of \( X_{pd} \), and \( F_{d} \) is the spatially averaged impact frequency of drops of size \( d \) impacting within a distance of \( X_{pd} \) of the boundary (Kinnell, 2005). \( X_{pd} \) is given by the product of the time particles of size \( p \) remain suspended in the flow and flow velocity (\( u \)). Both the time the particles remain suspended and \( M_{pd} \) vary with flow depth (Kinnell, 1993). Kinnell (2001) undertook experiments to measure the distance 0.46 mm particles of sand and coal travel after being lifted into 7 mm deep flows by the impact of 2.7 mm drops travelling at near terminal velocity. These experiments established that, for 0.46 mm sand and these rain and flow conditions, \( X_{pd} = 0.2 u \) and \( M_{pd} \) was 10 mg when the depth of the sand was much greater than that which protects the underlying particles from drop impact. The mechanistic simulation model is based on these results.

In the mechanistic simulation model, drop impacts are generated randomly in time and space and disturb a 5 by 5 mm area of the bed. Particles are then lifted from the soil surface into a 9 by 9 mm cloud. Sand particles in the cloud move horizontally a distance equal to \( X_{pd} \) before returning to the bed. The mass of material in the cloud is determined by

\[
M_{pd} = M_{pd,M}(1 - H_{R}) + H_{R} M_{pd,POL}
\]

where \( M_{pd,M} \) is the mass of material lifted from bed when no loose material is present on the surface, \( M_{pd,POL} \) is the mass of material lifted from bed when the depth of loose material is sufficient to protect underlying particles from the effect of drop impacts, and \( H_{R} \) is the degree of protection provided by the loose particles. \( H_{R} \) has a maximum value of 1.0. When, as in the Shaw et al. experiments, the surface over which the particles are moving is not erodible, \( M_{pd,M} = 0 \), so that

\[
M_{pd} = H_{R} M_{pd,POL}
\]

Consequently, \( M_{pd} \) equals the amount of sand sitting in the 5 by 5 mm area impacted by the drop whenever \( H_{R} < 1.0 \), and equals 10 mg when \( H_{R} = 1.0 \).

Fig. 1 shows the results produced by simulations for a range of spatial densities in the source area varying 0.1–1.8 mg mm⁻². The curves in this figure are labelled with values of \( H_{R} \), the ratio of the spatial density in the source area to spatial density of 0.46 mm sand that produces complete protection to the underlying surface (0.4 mg mm⁻²) when 2.7 mm drops travelling at near terminal velocity impact 7 mm deep flows, and it is assumed that the drops disturb a 25 mm² area on the bed. The curves for \( H_{R} > 1.0 \) result from the discharge of 0.46 mm sand over the boundary of the source area remaining constant until the amount of material in the area within 20 mm of that boundary falls below 0.4 mg mm⁻². However, because the discharge at the end of the flume lags in time, the rate at which the sand is

![Figure 1](image.png)

**Figure 1** Temporal variation in the amount of 0.46 mm sand discharged produced by the simulation for various amounts of sand in the 100 mm long source area upstream of a 300 mm long non-eroding area for 2.7 mm drops at an intensity of 60 mm h⁻¹ impacting 7 mm deep flows when the flow velocity was 100 mm s⁻¹. The values under the peak values for each curve are for \( H_{R} \), the spatial density of sand in the source area relative to the spatial density that completely protects the underlying surface from drop impact.
discharged at the end of the flume may peak sometime after
the discharge from the source area falls and at a value below
the peak at which sand was discharged from the source zone
(Fig. 2). When $Hz < 1.0$, the rate at which sand is discharged
at the end of the flume is always less than the peak at which
sand was discharged from the source zone (Fig. 3).

Obviously, the conditions set for the simulations differ
from those in the experiments undertaken by Shaw et al.
in a number of ways (eg. factor of 10 for depth, 1.6–2.3
for flow velocity, spatially uniform rainfall intensity com-
pared with waves of rain moving up and down the flow line).
However, the results shown in Figs. 1–3 provide some indi-
cation of how the discharge of sand sized particles moving
downstream through raindrop impact stimulated saltation
from a source zone such as used in their experiments is
likely to be influenced by the spatial density of the particles
in that source area. In the simulations, when the spatial
density is less than that which produces a value of
$Hz = 1.0$, the duration of the discharge pulse does not vary
with variations in the spatial density in the source area
(Fig. 1) and the peak value increases linearly with $Hz
(Fig. 4). When $Hz > 1.0$, the duration of the pulse increases
with increases in the spatial density in the source area
(Fig. 1), and the peak value varies nonlinearly with varia-
tions in $Hz$ (Fig. 4). However, the pulses produced when $Hz$
varied between 1.0 and 4.5 (Fig. 2) are essentially triangular
in shape without the flat peak produced by the Shaw et al.
model when $M_g > M_0$. Also, Shaw et al. do not provide any
experimental data that show conclusively that their pulses
did have flat peaks when $M_g > M_0$. Arguably, this may be
attributed to the fact that the sediment was collected over
1 min periods in time. However, it is more likely that, as in
the simulations and in experiments with rain-impacted flows
over sand (Fig. 5), the movement of particles downstream
by raindrop impact stimulated saltation in their experiments
was more diffuse than assumed in the Shaw et al. model.

Figure 2  Temporal variation in the amount of 0.46 mm sand discharged at the boundary of the source zone (100 mm) and at the
end of the flume (400 mm) produced by the simulation when $Hz = 6$.

Figure 3  Temporal variation in the amount of 0.46 mm sand discharged at the boundary of the source zone (100 mm) and at the
end of the flume (400 mm) produced by the simulation when $Hz = 0.5$. 
Although the Shaw et al. model may not adequately deal with the effects of the spatial and temporal nature of raindrop impact on the downstream movement of particles moving by raindrop impact stimulated saltation, some concern exists about the rainfall simulations system used in their experiments. According to Shaw (pers. com.), the rainfall module produced rain over about a 20 cm by 20 cm area. With raindrop impact stimulated saltation, the particle travel rate depends on flow velocity and on how quickly a subsequent drop impact lifts up particles deposited at a point

Figure 4  The relationship between the peak amount of 0.46 mm sand discharged and $H_z$, the ratio of the spatial density of the sand in the source area relative to that which protects underlying particles from the effect of drop impact.

Figure 5  Photograph of surface in the apparatus used by Kinnell (1991) after 10 min of rain made up of 5.1 mm drops falling 11.2 m was applied at 64 mm h$^{-1}$ to a 5 mm deep flow with a flow velocity of 20 mm s$^{-1}$ when 0.2 mm sand was used as the eroding surface and a portion of the upstream area was filled with the sand stained black.
by a previous drop impact upstream. In natural rainfall, raindrop impact is spatially and temporally random but in the case where a band of rain moves up and down the flow line, the probability of a subsequent impact occurring in a given time is greater when the wave is moving downstream than up. Consequently, there is a tendency to sweep particles downstream when the wave is moving in that direction. It also encourages a flow wave. These issues are well understood by people who have design field rainfall simulators which use sweeping sprays; the sprays sweep at right angles to the direction of flow. Consequently, the rainfall simulation system used by Shaw et al. had characteristics that should be avoided when undertaking experiments on sediment transport by rain impacted flows.

References


