Sediment Transport by Medium to Large Drops Impacting Flows at Subterminal Velocity

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ABSTRACT

Dripper-type rainfall simulators producing water drops from drop formers (metal or plastic tubes) have been widely used in laboratory experiments. These rainfall simulators produce medium (2.0–3.5 mm) to large (>5.0 mm) raindrops and, in many cases, because of restrictions in the height of fall from the drop formers to the target, rain with drop impact velocities that are considerably less than terminal velocity. To answer the question “Can the results for drops impacting at low velocity be extrapolated to the terminal velocity situation using rainfall kinetic energy as an independent factor?” the results of rainfall simulator experiments with medium (2.7 mm) and large (5.1 mm) pendant drops impacting water flowing over surfaces of 0.2-mm sand and heights of fall 3 m and less are presented and compared with the results obtained when the drops fell 11.2 m. A linear relationship between sediment discharge and the expenditure of the kinetic energy of the rain in unit time was obtained with 2.7-mm drops but not with 5.1-mm drops. The results indicate that the departure from natural rainfall in terms of drop size and velocity is sufficient for data produced by dripper-type simulators using large drops to be not as useful in a practical sense as data produced by rainfall simulators that produce rain drop sizes and velocities that are closer to those observed in natural rainfall.

MATERIALS AND METHODS

The 0.2-mm sand was placed in a 500 mm wide box in a flume with a weir to control flow depth over the sand (Fig. 1) as described by Kinnell (1991). Rain was applied to the target from pendant drop formers (hypodermic needles [2.7-mm drops] or plastic caps fitted over these needles [5.1-mm drops]) spaced on a 25.4-mm grid in the bottom of a plexiglass box. The plexiglass box was moved slowly (4.2 mm s⁻¹) a horizontal distance of 250 mm back and forth along the line of the flow so that all points on the target area have equal probabilities of being impacted (Kinnell, 1991). Rainfall intensity was controlled by using a metering pump to supply water to the plexiglass box. A frame was manufactured that allowed the height of the rainfall simulator above the target to be adjusted between 1 and 3.6 m. In addition, the laboratory enabled the simulator to be installed 11.2 m above the target.

Experiments were undertaken with four to five different heights of fall holding flow depth constant and four to five different flow depths holding height of fall constant. Each experimental condition was replicated three to five times. In all cases flow velocity was held close to 20 mm s⁻¹ and rainfall intensity held close to 64 mm h⁻¹. In the apparatus shown in Fig. 1, flow depth is controlled by flow discharge and the height of the weir. Flow discharges were chosen so that flow velocity when no rain was applied was at 20 mm s⁻¹ at the chosen flow depth and the height of the weir adjusted to obtain that or close to that flow velocity. When rain was added, the rain bleed was used to compensate for the additional input of water and flow depth measured via a pressure transducer attached to the pressure port.

Kinnell (1991) observed that the discharge of sand from the experimental situation being considered varied directly with rainfall intensity and flow velocity. Some variation in flow velocity and rainfall intensity is inevitable and to minimize the effect of these variations on the analysis of the results, the sediment discharge data were adjusted to give the sediment discharge associated with a rainfall intensity of 64 mm h⁻¹ and a flow velocity of 20 mm s⁻¹. This adjustment was achieved by multiplying the observed sediment discharges by 1280 divided by the product of the observed intensity (mm h⁻¹) and observed flow velocity (mm s⁻¹). Consequently, variations in the adjusted sediment discharges for any given drop size were only caused by variations in flow depth and drop impact velocity.

RESULTS

Figure 2 shows the sediment discharges obtained with rain made up of 2.7-mm drops for three different heights of drop fall when flow depth was varied. Figure 3 shows...
the sediment discharges obtained with rain made up of 5.1-mm drops when flow depth was varied. In all cases the sediment discharge \( q_s \) to flow depth \( h \) relationship was linear taking the form

\[
q_s = bh + c
\]

[1]

where \( b \) is a empirical coefficient and \( c \) is an empirical constant. The absolute ratio of \( c \) to \( b \) gives the value of flow depth that would give a sediment discharge of zero \( h_0 \) if Eq. [1] is extrapolated well beyond the range of flow depths used in the experiments. The values of \( h_0 \) are 6.67, 8.26, and 9.29 mm for 2.7-mm drops with fall heights 1, 3, and 11.2 m respectively, 15.0, 18.93, and 21.92 mm for 5.1-mm drops with fall heights of 1, 3.6, and 11.2 m, respectively. However, it should be noted that sediment discharges greater than zero occur at these and deeper flow depths (Kinnell, 1991, 1993) so that Eq. [1] should not be extrapolated much beyond the maximum depths used in these experiments.

Drop kinetic energies are given by 0.5 times the product of drop mass and the square of drop velocity. Drop velocities used in the calculation of kinetic energy in the current experiments were calculated from basic physical principles (Wang and Pruppacher, 1977) together with the drag coefficients of Wenzel and Wang (1970). The kinetic energy of rainfall can be expresses on a unit volume of rain (J m\(^{-2}\) mm\(^{-1}\)) basis or on a unit time basis (J m\(^{-2}\) s\(^{-1}\)). In terms of examining the relationship between sediment discharge expressed in units of mass per unit width per unit time, and rainfall kinetic energy, the unit time form should be used.

Figures 4 and 5 show how the sediment discharges associated with the two drop sizes varies with respect to the expenditure of the kinetic energy of the rain in unit time when flow depth was held constant. In the case of 2.7-mm drops, sediment discharge increases linearly with the expenditure of the kinetic energy of the rain in unit time. In contrast, the increase in sediment discharge associated with an increase drop impact velocity declines with the expenditure of the kinetic energy of the rain in unit time in the case of 5.1-mm drops.

**DISCUSSION**

As noted earlier, rainfall kinetic energy can be expressed in two forms, the kinetic energy per unit quantity of rain \( E_{\text{vol}} \) J m\(^{-2}\) mm\(^{-1}\)) and the kinetic energy per unit time \( E_{\text{time}} \) J m\(^{-2}\) s\(^{-1}\). The two are related to each other by the equation

\[
E_{\text{time}} = IE_{\text{vol}}
\]

[2]

where \( I \) is rainfall intensity. While raindrop kinetic energy varies with drop mass when drop velocity remains constant, rainfall kinetic energy does not. The reason
for this is that $E_{vol}$ is given by 0.5 times the product of drop mass, drop velocity squared, and the number of drops that contributes to the volume of water in 1 mm of rain. Any variation in drop mass is completely counterbalanced by the variation in the number of drops that contributes to the volume of water in 1 mm of rain. Also, 1 mm of rain on 1 m² has a mass of 1 Kg. As a consequence,

$$E_{vol} = 0.5 \, v^2$$  \[3\]

when $E_{vol}$ has units of J m⁻² mm⁻¹ and drop velocity ($v$) has units of m s⁻¹. Consequently, when, as in the case of the current experiments, rainfall intensity is held constant, variations both $E_{vol}$ and $E_{time}$ are directly related to drop velocity squared alone.

The 0.2-mm sand is transported in rain-impacted flows through a saltation process that results from the combined action of raindrop impact and the flow. This transport process has been referred to raindrop-impact induced flow transport (Kinnell, 1990). In simple terms, particles lifted into the flow by a raindrop impact travel an average downstream distance ($X_{pd}$, Fig. 6) that depends on particle-size and density, the height to which the particles are lifted ($z$, Fig. 6) and flow velocity. As a consequence, the sediment discharge of particles of size $p$ associated with drops of size $d$ is given by (Kinnell, 1991)

$$q_s(p,d) = M_{pd} \, X_{pd} \, F_d$$  \[4\]

where $M_{pd}$ is the mass of sand particles of size $p$ lifted by drops of size $d$, and $F_d$ is the spatially averaged impact of drops of size $d$ within the distance $X_{pd}$ of the downstream boundary. No sediment discharge occurs unless there is a drop impact within the distance $X_{pd}$ of the downstream boundary. In the experiments reported here, $F_d$ for each drop size is held constant while both $M_{pd}$ and $X_{pd}$ are influenced by variations in flow depth and drop impact velocity. The absorption of raindrop energy in impacting the water layer reduces the energy available to lift particles into the flow and this increases with flow depth. The decline in sediment discharge as flow depth increases is usually attributed to this effect. Given that rainfall kinetic energy is often considered as a primary independent variable in erosion models, there is an expectation that sediment discharge should vary directly with the expenditure of the kinetic energy of the rain in unit time. Although the results for 2.7-mm drops do conform to that expectation, the results presented here for 5.1-mm drops do not.

Initially, the results obtained with 5.1-mm drops appear to conflict with the observations of Moss and Green (1987) that sediment discharges produced by rain made up of 5.1-mm drops impacting 4.25 mm deep and 10 mm deep flows over 0.2-mm sand were linearly related to the kinetic energy of the rainfall. However, that analysis was restricted to rainfall kinetic energies produced with heights of fall of <2.4 m and arguably, there is a linear trend between sediment discharge and the expenditure of the kinetic energy of the rain in unit time for the 1- to 2-m range of fall heights in the current data set (Fig. 7). Also, extrapolating the trends observed by Moss and Green (1987) to the rainfall kinetic energy for 11.2-m fall produces much higher sediment discharges than they obtained for that fall distance.

It is apparent from Fig. 4 and Fig. 5 that the efficiency of the utilization of raindrop energy in the sediment transport process as drop velocity varies differs significantly...
between the two drop sizes studied and that this must relate to a difference in how the drops interact with the water layer. Large drops are inherently less stable than small drops. As noted by Moss and Green (1987), large drops traveling at high velocity disrupt on impact with water surfaces, creating cavities, coronas and Rayleigh jets while small drops and large low velocity drops impact with less disruption and transmit energy more efficiently to the bed. The effect of drop size on the form of the sediment discharge—the expenditure of the kinetic energy of the rain in unit time relationship also depends on some extent on flow depth. Kinnell and Wood (1992) observed that below a certain flow depth, sediment discharge produced by raindrops 2.7 mm in size and larger impacting at near terminal velocity did not vary with drop size. The 5-mm depth of flow common to the experiments with 2.7- and 5.1-mm drops is close to that flow depth. That fact contributes to the nonlinearity of the relationship between sediment discharge and the expenditure of the kinetic energy of the rain in unit time shown in Fig. 5. However, although it follows from Fig. 3 that that nonlinearity would be less severe with a deeper flow, a linear relationship between sediment discharge and the expenditure of the kinetic energy of the rain in unit time would not be achieved for a flow depth of three drop diameters or less with 5.1-mm drops over the 1- to 11.2-m range of fall heights considered here. Medium to large drops traveling at terminal velocity produce cavities about three to four drop diameters deep (Engel, 1966; Cai, 1989).

CONCLUSIONS

Rainfall simulators producing pendant drops from drop formers usually produce medium to large raindrops and no small drops but often produce rainfall kinetic energies similar to natural rainfall because restrictions in drop fall distance result in drop velocities that are lower than in natural rainfall. The results of experiments with rain made up of uniform medium to large sized drops impacting flows over sand reported here indicate that the relationship between sediment discharge and rainfall kinetic energy resulting from variations in drop velocity varies with drop size. The results indicate that the departure from natural rainfall in terms of drop size and velocity is sufficient for data produced by dripper-type rainfall simulators using large drops to be not as useful in a practical sense as data produced by rainfall simulators that produce rain drop sizes and velocities that are closer to those observed in natural rainfall.

REFERENCES