Raindrop Interaction in Interrill Erosion for Steady Rainfalls: a Probabilistic Approach

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Abstract

The main processes involved in interrill erosion are soil particles detachment and transport. Detachment is caused by shear stresses created by the impacts of raindrops. After sediments are lifted in the water layer, they are transported over a distance that depends on their settling velocities and the water flow velocity. This study calculates the probabilities of interactions between raindrops during soil detachment, and between raindrops and particles during their sedimentation. Raindrops are assumed to be consistent with the Poisson process and their densities are described by raindrop size distribution functions (Marshall-Palmer, Gamma and Lognormal laws). Interaction probabilities are calculated based on characteristic time and length scales of the shear stresses and the perturbation created by the raindrop impact inside the water layer.

Under the hypothesis of a constant rainfall intensity, the results show that, during soil detachment, raindrops are almost independent. Thus, the total amount of soil detached by a rainfall is practically the sum of soil detached by its individual raindrops. Whereas during sediment transport, the probability of interaction between raindrops and settling particles is very high whatever the rainfall intensity and particle size, emphasizing the need to study further the interaction between raindrops and settling particles.

Keywords: Raindrop, Poisson process, shear stress, shallow water flow, detachment, sedimentation, soil erosion.

1 Introduction

In interrill erosion, raindrop impact is the major agent causing soil detachment and transport (*Ellison*, 1944; *Ghadiri and Payne*, 1981; *Aldurrah and Bradford*, 1982). During the impact, the drop exerts a lateral force on the soil surface that is converted to shear stress. This impact shear stress breaks soil aggregates (*Ghadiri and Payne*, 1977) and leads to sediment detachment which is the separation of soil particles from the soil matrix (*Ellison*, 1944). The extent of the area affected by the impact of the raindrop depends both on the soil and raindrop properties (grain size and raindrop diameter) as shown experimentally by *Furbish et al.* (2007). *Leguédois and Le Bissonnais* (2004) and *Legout et al.* (2005) also showed through experimental studies that the characteristics of the soil control the size of the particles that are detached and transported in the air by splash. The sediments transported by splash are then distributed radially around the impact area over a few decimeters (*Leguédois et al.*, 2005) and their mass decreases exponentially from this area (*Van Dijk et al.*, 2002). When a water layer covers the soil surface, the detached particles are also transported downstream by the sheet flow in interaction with raindrops (*Kinnell*, 2005).

   Salles et al. (2000) and *Ferreira and Singer* (1985) assumed that the effect of a rainfall is the sum of the individual drops effects, implying that the amount of soil detached by a rain is the addition of soil particles detached by all its individual raindrops. Similarly, *Sharma et al.* (1993) proposed a model of soil detachment caused by rainfall by summing the individual kinetic energy of raindrops. *Gilley et al.* (1985) related the amount of soil detached from several raindrops to the sum of their maximum impact pressures. Hence, all these authors consider that there is no interaction among raindrops during soil detachment caused by shear stresses. Nevertheless, there is no study, to our knowledge, which establishes the independence of the shear stresses caused by individual raindrops. Even if the time period between the impact of two drops is quite large compared to splash duration (*Wang and Wenzel* (1970) quoted by *Ferreira and Singer* (1985)), it is not necessarily the case when considering shear stress duration. Indeed, the shear stress can last a long time for large drops and for a thick water layer as shown by *Hartley and Julien* (1992) through a numerical description of the shear stress created by a drop impacting a water layer.

   In the context of interrill erosion, it is widely recognized that raindrops cause a continuous lifting of sediments from the soil to the flow (*Kinnell*, 1991; *Hairsine and Rose*, 1991) and a mix of sediments inside the water layer (*Proffitt et al.*, 1991). However, the interaction between raindrops and settling particles is not well established.

   Obviously, rainfall characteristics have a major control on interrill erosion. In atmospheric science, rain is usually described by a drop size distribution function that estimates the number of drops of a given diameter in 1 m^3 of air. The most well-known distribution is the Marshall-Palmer law (*Marshall and Palmer*, 1948), generally valid for stratiform rains. Other distributions, such as the Gamma law (*Ulbrich*, 1983) and the Lognormal law (*Feingold and Levin*, 1986), have also been used to describe a wider range of rains including shower, thun-

derstorm, stratiform, and orographic rains. Regarding raindrop interactions, another important characteristic of the rain is the falling process of its drops. In the literature, different processes have been used to describe the distribution of natural raindrops. Among these processes, the most used are the Poisson process (*Gillespie*, 1972, 1975; *Hosking and Stow*, 1987; *Uijlenhoet et al.*, 2006; *Ma et al.*, 2008; *Uijlenhoet et al.*, 2009), the Cox process (*Cox and Isham*, 1980; *Sasyo*, 1965; *Smith*, 1993) and the fractal description (*Lovejoy and Schertzer*, 1990; *Lavergnat and Golé*, 1998; *Lilley et al.*, 2006). In the present study, we focus on steady rainfalls which has been demonstrated to be consistent with the Poisson process (*Uijlenhoet et al.*, 2006; *Jameson and Kostinski*, 2001). In this case, the rain is statistically stationary as shown by *Jameson and Kostinski* (2002) and raindrops are uniformly distributed. The spatial and temporal distribution of raindrops are described by the Poisson process, which has the advantage to be simpler than the Cox and the fractal descriptions. Moreover, for natural rainfall, some authors like *Uijlenhoet et al.* (2006, 1999) and *Larsen et al.* (2005) show through experimental studies that a rainfall can be decomposed in stationary periods where the Poisson process is valid.

The purpose of this work is to verify if interactions between raindrops during soil detachment, and between raindrops and settling particles have to be taken into account for interrill erosion. We use a common probabilistic framework for both detachment and transport to calculate probabilities of interaction. Our study considers steady rainfalls which are consistent with the Poisson process and uses the Marshall-Palmer, Gamma and Lognormal laws. These laws are detailed in section 2.2. Sections 2.3 and 2.4 present the time and length scales required to evaluate the possible zone of interaction for the detachment and transport processes. Then the methodology used to calculate the total interaction during a rainfall for each process is presented. Finally, in section 3, the different probabilities of interaction are shown and discussed.

2 Materials and Methods

2.1 Problem Configuration

Interrill erosion takes place on a soil covered by a thin water layer of depth h (Figure 1). It is characterized by a flow of low velocity $\mathbf{u} = u\mathbf{e}_x$ struck by raindrops with various diameters D. When impacting the water layer, each drop can create a shear stress that we consider to be transmitted instantaneously at the soil surface, which can detach soil particles. The shear stress extends on a region of radius x_r (Figure 1). In interrill erosion, all suspended particles come from raindrop detachment. After being suspended, sediments remain in the water for a duration t_s related to their settling velocity w_s and the water layer depth h. We are interested in two cases: (1) the interaction between drops during shear stress creation, and (2) the interaction between drops and settling particles. The study area in the (x, y) plane is taken large enough to detect at least one drop.

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2.2 Rain Properties

2.2.1 Poisson Process

We are interested in estimating the number of raindrops with diameters D between D_1 and D_2 that hit a surface S during some time t. This defines a set Ω whose size is measured in $\text{m}^2 \times \text{s} \times \text{mm}$ (surface unit, time unit and length of the interval $[D_1, D_2]$). This number can be viewed as a random variable N_Ω on the space of possible rain events, and we wish to estimate the probability $P(N_\Omega = k)$ that k drops are in Ω for $k = 0, 1, 2, \ldots$.

A classical model for such a counting process is to assume that it follows a Poisson process. This implies in particular that the law of N_Ω is completely determined by a single number $\alpha > 0$, called the Poisson parameter. More precisely, we have

$$P(N_\Omega = k) = \frac{\alpha^k}{k!} e^{-\alpha}, \qquad \text{for } k = 0, 1, 2, \ldots.$$

Our goal is to estimate this parameter α.

Several conditions are required to justify the use of the Poisson process (*Goodman*, 1985; *Ochi*, 1990). In particular, the probability of having more than one drop in a set Ω (as defined above) must vanish as the size of Ω goes to zero. Another fundamental property is that, for two disjoint sets Ω_1 and Ω_2 the random variables N_{Ω_1} and N_{Ω_2} must be independent. This means somehow that raindrops are uncorrelated in terms of localization, time and diameter distribution. It has been evidenced that this is achieved for steady rains whose intensities are independent of the measurement point (*Uijlenhoet et al.*, 1999; *Jameson and Kostinski*, 2002; *Larsen et al.*, 2005).

Therefore, from now on we assume that the raindrops follows a Poisson process of parameter α. This parameter α is actually the averaged number of drops over all the rains under consideration, or, in other words, the expectation of the random variable N_Ω. The following sections are devoted to the physical modeling of raindrops interactions. As we shall see, the model we obtain actually does not depend on the rain event itself, but merely on physical properties of the raindrops. This implies that the averaged number α can be computed once for all by considering one arbitrary rain.

2.2.2 Raindrop Size Distributions

A raindrop size distribution gives the number of drops as a function of diameter in a volume of air. We consider three usual raindrop size distributions.

1. The first one is the Marshall-Palmer law, which is a negative-exponential distribution (*Marshall and Palmer*, 1948). It is one of the exponential distributions proposed by *Kostinski and Jameson* (1999) to give a good description for steady rains, which follow the Poisson statistics. The Marshall-Palmer size distribution is given by:

$$N_v(D) = N_0 \exp(-\lambda D), \quad \text{with} \quad \lambda = 4.1 I^{-0.21}, \tag{1}$$

where I is the rainfall intensity (mm h^{-1}) and $N_0 = 8000$ (mm^{-1}m^{-3}) is the value of N_v for $D = 0$ (*Brodie and Rosewell*, 2007). Consequently, the number of drops in 1 m^3 of air with a diameter in the class between D and $D + dD$ (where D, dD are in mm) is given by $\int_D^{D+dD} N_v(x)dx$, which can be approximated by $N_v(D)dD$ provided dD is small enough.

Equation (1) is the result of a large collection of data from stratiform rains of intensities up to 23 mm h^{-1} (*Marshall and Palmer*, 1948). However, this law has been used for rainfall intensities as high as 200 mm h^{-1} (*Hall and Calder*, 1993). Finally, we note that *Houze et al.* (1979) showed it gives good description of raindrops at ground level.

Two other raindrop size distributions are also considered:

2. The second one is the Gamma law of *Ulbrich* (1983):

$$N_v(D) = N_0 D^\beta \exp(-\lambda D) \tag{2}$$

where $\lambda = (3.67 + \beta)/D_0$, $D_0 = \epsilon I^\delta$ is the median volume diameter, and N_0 (m^{-3}cm$^{-1-\beta}$), β, ϵ and δ are parameters defining the shape of the raindrop size distribution. In this study we consider $N_0 = 6.4 \times 10^{10}$ m^{-3}cm$^{-1-\beta}$, $\beta = 4.65$ and $D_0 = 0.114 I^{0.11}$ cm (see (*Ulbrich*, 1983)).

3. The third law is the Lognormal law of *Feingold and Levin* (1986):

$$N_v(D) = \frac{N_T}{\sqrt{2\pi}\ln\sigma D} \exp\left[-\frac{\ln^2\left(\frac{D}{D_g}\right)}{2\ln^2\sigma}\right] \tag{3}$$

where $N_T = 172 I^{0.22}$, $D_g = 0.72 I^{0.23}$ and $\sigma = 1.43$.

The Lognormal and Gamma laws are usually used for an instantaneous description of a rain whereas exponential distributions (typically the Marshall-Palmer law) are used to describe the space- or time- average of several individual rainfalls (*Joss and Gori*, 1978). The effect of these three laws on the probabilities of interaction will be studied, but one could choose any other law for $N_v(D)$.

Being given the raindrop size distribution, the density of drops reaching the ground is estimated with (*Hall and Calder*, 1993; *Brodie and Rosewell*, 2007):

$$N_a(D) = N_v(D)V_f(D), \tag{4}$$

where D is in millimeters and $V_f(D)$ is the terminal velocity of the drop (m s^{-1}), estimated thanks to the formula of *Uplinger* (1981)

$$V_f(D) = 4.854 D \exp(-0.195 D). \tag{5}$$

Consequently, the number of drops with a diameter between D and $D + dD$ that hit a surface S is $\int_S \int_D^{D+dD} N_a(D)dDdxdy$.

The most numerous drops at the ground can be identified by their relative frequency, that is by dividing the frequency of each class of drops by the total number of drops reaching the ground. The shape of the relative density of drops $S_a(D)$ depends on the raindrop size distributions (Figure 2):

$$S_a(D) = \frac{N_a(D)}{\displaystyle\int_{D_{min}}^{D_{max}} N_a(x)dx}.$$ (6)

2.3 Particle Detachment

2.3.1 Time and Length Scales for a Single Drop

The shear stress at the soil surface caused by a raindrop depends on the depth of the water layer (*Nouhou Bako et al.*, 2016). The area affected by the shear can extend over a circle much larger than the impacting drop size (*Ghadiri and Payne*, 1977). *Wang and Wenzel* (1970)'s work estimated the size of this area to be 10 times the drop diameter. In all cases the shear duration is quite short. According to *Ghadiri and Payne* (1977) its lasts for some milliseconds at most. Both *Hartley and Julien* (1992) and *Hartley and Alonso* (1991) reported numerical studies of the shear stress caused by the impact of a drop. We make use of their mathematical description of the instantaneous shear stress. Their equations estimate the local shear stress caused by a drop of radius R striking a water layer of depth h with a velocity V_0. They used a β-function to describe the spatial distribution of the shear stress. Equation (7) describes the maximum influenced radius x_r of the shear:

$$x_r(R,h) = R\{1 + 7.5[1 - \exp\left(-0.63\frac{h}{R}\right)]\}.$$ (7)

The time t_r to reach maximum shear stress is given by:

$$t_r(R,h) = 1.4\frac{R}{V_0}\left(\frac{h}{R}+1\right)\left[1 - \exp\left(-0.6\frac{R\theta}{h}\right)\right],$$ (8)

with

$$\theta = \theta(R) = \frac{FW^{0.5}}{F + W^{0.5}},$$ (9)

where $F = V_0(gR)^{-1/2}$ and $W = \rho V_0^2 R/\gamma$ are the Froude and Weber numbers based on the fluid density ($\rho = 1000 \text{ kg m}^{-3}$), the surface tension ($\gamma = 0.02 \text{ kg s}^{-2}$) and gravity ($g = 9.81 \text{ m s}^{-2}$).

Although equations (7)–(8) have been obtained for low Reynolds numbers ($50 < Re < 100$), *Hartley and Alonso* (1991) extrapolated them by experimental studies to Reynolds numbers of natural rainfalls ($6500 < Re < 23000$). Here, we will use equations (7)–(8) for natural raindrops to estimate the extent and duration of the shear stress, with the raindrop velocity V_0 taken equal to its terminal velocity V_f, and the maximum duration of the shear t_{max} equal to $16t_r$, based on *Hartley and Alonso* (1991) who estimated the duration of the shear stress to range from $6t_r$ to $16t_r$.

2.3.2 Estimation of the Poisson Parameter

Our goal is to evaluate if the shear stress caused by a first drop P, called primary drop, with a diameter D_p, can interact with the shear caused by another drop S, called secondary drop, with a diameter D_s. The first step is to identify and count the secondary drops likely to cause this interaction. These secondary drops are contained in a set of influence that allows them to interact with the shear stress of the primary drop. The primary drop influences an area of $S_p(D_p, h) = \pi[x_r(\frac{D_p}{2}, h)]^2$ lasting for t_{max}. So, the set of influence looks like a cylinder (Figure 3) and its size is given by:

$$\Omega_{sp}(D_p, D_s, h) = S_p(D_p, h)t_{max}(D_p, h)V_f(D_s) \tag{10}$$

where $V_f(D_s)$ is the terminal velocity of the secondary drop. Overall, each type of secondary drops S (with different diameters and consequently different terminal velocities V_f) defines a different set of influence with a size Ω_{sp} in which the secondary drops can interact with the shear caused by the primary drop.

As the secondary drops follow the Poisson process, we can estimate the average number of drops α_{sp} in the set Ω_{sp}. The parameter α_{sp} is evaluated using any of the raindrop size distribution N_v defined in Section 2.2.2:

$$\alpha_{sp}(D_p, D_s, h) = \Omega_{sp}(D_p, D_s, h)N_v(D_s) = S_p(D_p, h)t_{max}(D_p, h)N_a(D_s) \tag{11}$$

where $N_a(D_s)$ is given by equations (4)–(5).

2.3.3 Total Probability of Interaction for a Rainfall

To compute the total probability of interaction between the raindrops of a rainfall we consider two steps. The first step is to calculate, for each class of diameter D_p of the primary drop P, the probabilities of interaction with all classes of secondary drops S (of different diameters D_s and terminal velocities V_f). Because each class of secondary drops follows the Poisson process, this probability is given by:

$$P_{D_p \longleftrightarrow S} = 1 - \exp(-\int_{D_{min}}^{D_{max}} \alpha_{sp}dD_s) \tag{12}$$

where α_{sp} is the average number of drops S in Ω_{sp} for each class likely to create shear stress.

This quantity $P_{D_p \longleftrightarrow S}$ has to be understood as the conditional probability of interaction for a primary drop, being given the diameter D_p. In this context, the total probability P_t of interaction between all the classes of primary drops P and secondary drops S is obtained by integrating $P_{D_p \longleftrightarrow S}(D_p)$ with respect to the relative density of primary drops $S_a(D_p)$:

$$P_t = \int_{D_{min}}^{D_{max}} [P_{D_p \longleftrightarrow S}S_a(D_p)]dD_p = 1 - \int_{D_{min}}^{D_{max}} [\exp(-\int_{D_{min}}^{D_{max}} \alpha_{sp}dD_s)S_a(D_p)]dD_p. \tag{13}$$

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Moreover, when the water depth is larger than three drop diameters, no detachment occurs because the water layer protects the soil from the raindrop effect (*Mutchler and Young*, 1975; *Wang and Wenzel*, 1970). Therefore, we use $h = 3D$ as a threshold: when $h \geq 3D_p$ the primary drop does not cause shear, and hence the probability of interaction with secondary drops is zero. It is also the case if $h \geq 3D_s$ for the secondary drops. Therefore all the integrals in equation (13) becomes $\int_{max(D_{min}, h/3)}^{min(D_{max}, h/3)}$.

The quantity P_t estimates the probability of interaction between raindrops and the soil surface through the shear stress created by the raindrop. Note that a low probability of interaction P_t shows a lack of interaction whereas a high probability of interaction cannot assert the existence of an interaction: the exact magnitude of the shear stress is not accounted for, nor are the actual soil properties such as its shear strength. So, if the probability of interaction is high, we consider it as the probability of a potential interaction.

2.4   Particle Sedimentation

2.4.1   Time and Length Scales for Sedimentation

Soil particles, after being detached from the soil matrix, enter in the water layer and are then transported by the water flow. During their transport into the flow, *i.e.* before they reach back the soil surface, they can interact with raindrops. To calculate this probability of interaction we make two assumptions. The first one is that the vertically-falling raindrops perturb the water layer instantaneously because the water depth is very small compared to the lateral extent of the perturbation. Thus, only the horizontal perturbation has to be taken into account. The second assumption is that the occurrence of particles in the water layer obeys a Poisson process. This assumption can be made because (1) particles appear in the water layer randomly and (2) particle concentration in interrill erosion is always very low (of the order of 10 g L^{-1} (*Proffitt et al.*, 1991; *Asadi et al.*, 2007; *Tromp-van Meerveld et al.*, 2008)), so that particles are unlikely to interact together and hence can be considered as independent.

The average suspension duration t_s of each particle is estimated by the ratio between the water layer depth h and the particle settling velocity w_s: $t_s = h/w_s$. There are a lot of laws for the settling velocity in the literature (*Dietrich*, 1982; *Turton and Clark*, 1987; *Cheng*, 1997; *Zhiyao et al.*, 2008), including the Stokes' law (*Stokes*, 1880), which is valid only in laminar regime. Among these laws we choose the equation of *Cheng* (1997) because *Fentie et al.* (2004) shown that it seems to be the best formula:

$$w_s(d) = \frac{\mu_l}{d} \left(\sqrt{25 + 1.2 d_*^2} - 5 \right)^{1.5}, \tag{14}$$

where $d_* = \left(g\Delta/\mu_l^2 \right)^{1/3} d$, with $\mu_l = 10^{-6}$ m^{2}s^{-1} the water kinematic viscosity, d the particle diameter, $g = 9.81$ m.s^{-2} the gravity, $\Delta = (\rho_s - \rho_l)/\rho_l$ the relative density ($\rho_l = 1000$ kg m^{-3} is the water density and ρ_s is the particle density).

A raindrop striking the water layer creates a perturbation spreading with a radius R_s. *Josserand and Zaleski* (2003) and *Nouhou Bako et al.* (2016) showed that the expansion law of R_s can be approximated by $R_s = \sqrt{DV_f t}$ with D the drop diameter, V_f its terminal velocity and t the time. The main physical quantities acting during the disturbance are the surface tension γ, the water density ρ_l and the drop diameter D. These parameters are used in dimensional analysis to estimate the total duration of the perturbation. This leads to the duration t_c, called capillary oscillation time, estimated with the formula $t_c = \sqrt{\frac{\rho_l D^3}{\gamma}}$. After t_c, the perturbation disappears because of the surface tension. So, the maximum radius reached by the perturbation is $R_{max} = \sqrt{DV_f t_c}$ and its average speed of propagation is $V_m = R_{max}/t_c$.

For this study, we take soil particles in aggregated form with a bulk density $\rho_s = 1300$ kg m^{-3} (*Chepil*, 1950; *Kinnell*, 2001) and with a size smaller than 2 mm. Because interrill erosion is characterized by a very thin water layer, we limit the largest particle size to 2 mm so that the particles are completely included into the water layer. For simplification, we also consider the particles in the water layer not to be a mixture of different particle sizes but having a single size.

2.4.2 Estimation of the Poisson Parameter

When a drop strikes the water layer, its perturbation spreads in the horizontal direction. As explained before we assume that the water layer is thin enough to be vertically perturbed instantaneously. We also take the water flow at rest for simplification. This assumption is realistic because the interrill area is characterized by low flow velocity of the order of a few centimeters per second.

The radius of the raindrop perturbation evolves as $R_s = \sqrt{DV_f t}$ until it reaches $R_{max} = \sqrt{DV_f t_c}$ in the (x, y) plane (Figure 4). During the perturbation, the settling of each particle included in the area of radius R_s will be influenced by the drop. Taking into account the average suspension duration of a class of particles t_s, we can establish the domain where their sedimentation can be influenced by an incoming raindrop. This domain can be drawn in time-space coordinates (Figure 5). The total maximum volume V_t of this region can be seen as the sum of two contributions: a paraboloid V_1 and a cylinder V_2. The paraboloid V_1 is related to the circular expansion of the raindrop perturbation with time: $V_1 = \frac{1}{2}\pi R_{max}^2 t_c V_m$. The cylinder V_2 represents the suspension duration: it combines the average suspension duration of particles and the raindrop maximum perturbation radius: $V_2 = \pi R_{max}^2 t_s V_m$. Finally, all the particles in the volume $V_t(D) = V_1 + V_2$ (that corresponds to the paraboloid V_1 with a time translation of t_s) interact with the raindrop.

So, the Poisson parameter of the Poisson process for a drop of diameter D_i is calculated as:

$$\alpha_{ip} = V_t(D_i)N_p, \tag{15}$$

where N_p is the ratio between the particle concentration (g L^{-1}) in the water layer and the mass (g) of one particle. Hence, N_p represents the number of

particles per volume unit.

2.4.3 Probability of Interaction between a Rainfall and the Settling Particles

The total interaction for a rainfall is computed by first calculating the probability of interaction between a particle class p and the drops in the class of diameter D_i. This probability is calculated with the following equation:

$$P_{p \leftrightarrow D_i}(k \geq 1) = 1 - \exp(-\alpha_{ip}). \tag{16}$$

Then, as in the case of the interaction between raindrops during shear stress creation, we combine equation (16) with the relative density $S_a(D_i)$ of the drops at the ground. Expressing $P_{p \leftrightarrow D_i}$ as a conditional probability, this gives the total probability P_p of interaction between the particle class p and all raindrop diameters:

$$P_p = \int_{D_{min}}^{D_{max}} [P_{p \leftrightarrow D_i}(k \geq 1)S_a(D_i)]dD_i = 1 - \int_{D_{min}}^{D_{max}} \{\exp[-V_t(D_i)N_p]S_a(D_i)\}dD_i \tag{17}$$

As in the section 2.3.3, if the probability P_p is high, we consider it to be the probability of a potential interaction.

2.5 Calculation Parameters

The calculation of the probabilities P_t and P_p are done using the Marshall-Palmer, Gamma and Lognormal laws with a diameter step of $dD = 0.01$ mm because preliminary calculations showed this value was small enough to be close to the convergence of the law. We consider raindrop diameters ranging from D_{min}=0.25 mm to D_{max}=6 mm. First, the number of raindrops smaller than 0.25 mm is always very low for the Gamma and Lognormal laws (Figure 2). Moreover, we assume that drops smaller than 0.25 mm have such limited energy that they cannot cause significant detachment or transport. Finally, drops larger than 6 mm are extremely rare in rainfalls whatever the raindrop size distribution (Figure 2). We explore intensities ranging from 5 to 200 mm h^{-1} and water layer depth h ranging from 1 mm to 15 mm.

3 Results and Discussions

3.1 Total Interaction for Particle Detachment during a Rainfall

The total interaction for particle detachment during a rainfall is calculated for all the range of water layer depths and rainfall intensities. For the Marshall-Palmer law, the total probability of interaction increases with rainfall intensity (Figure 6). When the water layer is very thin, small drops (larger than $h/3$)

can create shear stress and hence contribute to detachment. But a thin water layer limits the shear stress extent and its duration. So, the total probability of interaction between raindrops is small even if a large number of drops is involved. For example, for a rainfall intensity $I = 100$ mm h^{-1} and a water layer depth $h = 1$ mm, the total probability of interaction is around 0.3% (Figure 6). When h increases, both the shear extent area and its duration increase. Thus, the probabilities of interaction increase when the water layer depth increases up to a maximal value. This maximal value depends on the rainfall intensity and is about 2 mm for $I \leq 40$ mm h^{-1} and 3 mm for $I \geq 40$ mm h^{-1}. These maximal values depend on both the water depth and the rainfall intensity: For a given water depth, a higher rainfall intensity provides more numerous large drops, and these large drops allow for higher interactions. With the increase in water depth, the shear created by these large drops fill a larger area and persist for a longer time. For water layers larger than 2–3 mm, the probabilities decrease with the water layer depth. Indeed, for thicker layers, the proportion of raindrops creating shear stress at the soil surface decreases significantly. Overall, for the Marshall-Palmer law, all probabilities are very low (less than 1.2%) even for a rainfall intensity as high as 200 mm h^{-1}.

The probability of interaction was also evaluated for raindrop size distributions following the Gamma law (equation (2)) and the Lognormal law (equation (3)). Probabilities from these laws are larger than for the Marshall-Palmer law (Figures 7 and 8), but their qualitative behaviors are quite similar. The depth at which the most important interaction takes place is equal to $h = 3$ mm for the Gamma law independently of the intensity. For the Lognormal law, this depth is a function of the rainfall intensity: when the intensity I is smaller than 20 mm h^{-1}, the highest probabilities are for $h = 3$ mm; for an intensity between 20 mm h^{-1} and 55 mm h^{-1}, the maximum occurs at $h = 4$ mm, then at $h = 5$ mm for an intensity between 55 mm h^{-1} and 130 mm h^{-1} and, finally, at $h = 6$ mm for an intensity larger than 130 mm h^{-1}. The differences among the laws are explained by the diameter of the most numerous drops reaching the ground. For example, let us consider all the classes of drops for which $S_a > 10\%$. For the Marshall-Palmer law, the diameter of these most numerous drops ranges from 0.25 to 2.25 mm, quite close to the range of diameters (0.4 to 2.45 mm) for the Gamma law (Figure 2). However, their diameters range from 0.85 to 3.35 mm for the Lognormal law. Because the most numerous drops are larger for the Lognormal law than for the Marshall-Palmer and Gamma laws, a rain following the Lognormal law causes a maximum interaction for larger water depths.

Whatever the law of raindrop size distribution, the probability of interaction between raindrops remains limited, with a maximum value lower than 2.5% in the most extreme case. This result is consistent with the one of *Ma et al.* (2008) who showed that the proportion of the detached particles from the areas which have been impacted by more than one drop is about 2.6% for a rainfall intensity of 60 mm h^{-1}. The results of *Ma et al.* (2008) were based on the Poisson process and a Gamma distribution function and were supported by experimental studies.

Therefore, for interrill erosion and steady rains, the drop interaction during detachment is generally low and, as a consequence, detachments of soil particles

by individual raindrops are mostly independent. The present probabilistic approach confirms by analytical means that summing the detachment caused by individual drops allows to a proper estimate of the total amount of soil detached by a steady rainfall, as carried out by previous studies such as *Sharma et al.* (1993), *Gilley et al.* (1985) and *Ferreira and Singer* (1985).

3.2 Total Interaction for Particle Sedimentation during a Rainfall

The total probability of interaction between settling soil particles and rainfalls of different intensities is calculated for several classes of particles using first the Marshall-Palmer law. For a particle concentration of $c = 10$ g L^{-1} and a water depth equal to $h = 3$ mm, the probabilities of interaction for each class of particles increase with rainfall intensity (Figure 9). Indeed, at high intensities, the number of large drops allows for a large probability of potential interaction (larger than 75%). For a given rainfall intensity, the probability of interaction increases as the size of the particle decreases. Particles with a diameter lower than 500 μm may all interact with the rainfall whatever its intensity. This is consistent with the transport mode of the particles: Small particles move in the water layer by suspension allowing high interaction with raindrops whereas coarser particles move by saltation or rolling that reduce their suspension duration and therefore their probability of interaction with raindrops.

We also tested the effect of the concentration. For example, for particle size equal to 1500 μm, the probability of interaction of these particles with rainfall increases with their concentration and with rainfall intensity (Figure 10). These potential interactions have always a significant probability ($> 40\%$). Moreover, the effect of the concentration is the same as the effect of the water layer depth (not shown). Indeed, for a given particle size, increasing the concentration when keeping a constant water layer depth or increasing the water layer depth when keeping a constant concentration increase in both cases the number of particles in the influenced area, leading to a higher probability of potential interaction with the rainfall.

For the Gamma and Lognormal laws, the probabilities are all higher than for the Marshall-Palmer law, by about 20 % for 2000 μm particles (Figures 11 and 12). Moreover, the 100% probability is reached for a larger particle size, 1 mm and 1.5 mm for the Gamma and Lognormal laws respectively, instead of 500 μm for the Marshall-Palmer law. All the particles have an extremely high probability of potential interaction, especially for rainfall intensities larger than 60 mm h^{-1}. This potential interaction is the largest for the Lognormal law.

Whatever the law of raindrop size distribution, the probability of potential interaction between raindrops and settling particles is always large, with a minimum value of about 40% (at low rainfall intensity and low particle concentration). Therefore, for interrill erosion and steady rains, transport of soil particles could depend on the interaction between particles and raindrops. As

a consequence, the summing approach used for particle detachment may not be valid for particle transport.

In shallow water flow, the flow disturbance caused by raindrops can be compared to an effect of turbulence. However some studies in turbulence showed that settling velocities can be either increased, reduced or stay unchanged (*Wang and Maxey*, 1993; *Bagchi and Balachandar*, 2003; *Brucato et al.*, 1998). In soil science, *Tromp-van Meerveld et al.* (2008) and *Jomaa et al.* (2010) have modified the settling velocity in the Hairsine and Rose model (*Hairsine and Rose*, 1991, 1992) to improve their experimental results. The present study cannot state how the settling velocity is modified but shows that settling velocity could be affected by raindrops. The exact nature of the interaction between raindrops and settling particles need to be further investigated.

3.3 Extension to non-Poissonian rainfalls and to erodible soils

All the calculations were carried out under the assumption of a Poissonian rainfall. This allowed considering drop arrivals to be uncorrelated, but limited the scope of the study to rainfalls having an almost-constant rainfall intensity. In the case of a rainfall with a variable rainfall intensity, the raindrop arrivals are correlated. This means that raindrops could have a higher probability to interact during detachment, although the magnitude of the increase remains unknown. Potentially this could lead to invalidate the summing approach. For particle transport, the probability of potential interaction will also increase, but since it is already quite high, accounting for the interaction between particles and drops will remain required. It will also be the case if the occurrence of soil particles in the water layer is not a Poisson process.

The current approach accounts for the shear stress at the soil surface. However, it does not account for the shear strength of the soil surface. In case of a soil with a significant shear strength, the probability of interaction during detachment will be lower than our estimate because only a part of the shear stress applied to the soil surface will be efficient in detaching soil material. This could also lead to a time-dependent probability, owing to the changes in soil surface properties during sealing, crusting and shield layer development.

4 Conclusions

A probabilistic analysis of raindrop interaction was made for particle detachment and particle sedimentation in the context of interrill erosion. The rainfall and the sedimentation were assumed compatible with a Poisson process. Whatever the raindrop size distribution law (Marshall-Palmer, Gamma or Lognormal law), the probability of interaction between drops through their shear stress at the soil surface is always limited. Hence, for soil detachment, raindrops can be considered as independent. This justifies *a posteriori*, and independently

of previous studies, the summation of the quantities of sediment detached by individual raindrops used in some models of soil detachment.

The probability for a particle to be disturbed by a raindrop during its sedimentation is always very high, and is even equal to 100% for particles smaller than 500 μm (for the considered raindrop size distribution laws). Hence, the potential interaction between drops and particles cannot be ignored. If this potential interaction actually affects the particle settling, the summation approach will be impeded.

These conclusions are valid under the assumptions of a Poisson process and a steady rain intensity. For non-steady rains, for which the Poisson process approximation is not valid, the probability of interaction between raindrops during soil detachment could be increased, invalidating the summation approach for detachment. For particle sedimentation, the conclusions will remain valid because the probabilities of potential interaction were already very high for steady rains.

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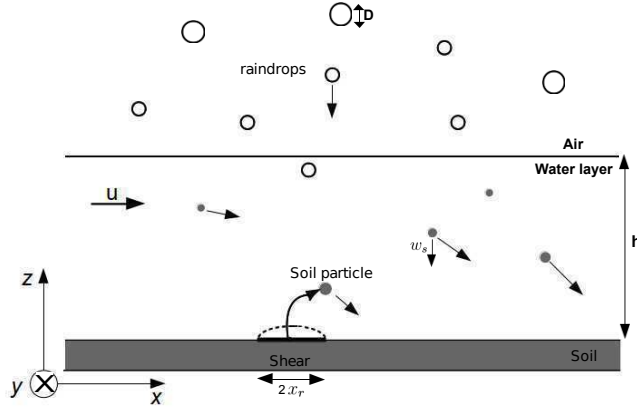
Figure 1: Configuration of a soil covered by a water layer having a flow velocity **u**. The water layer is impacted by raindrops which create shear stresses at the soil surface, causing particle suspension. Suspended particles settle down thereafter.
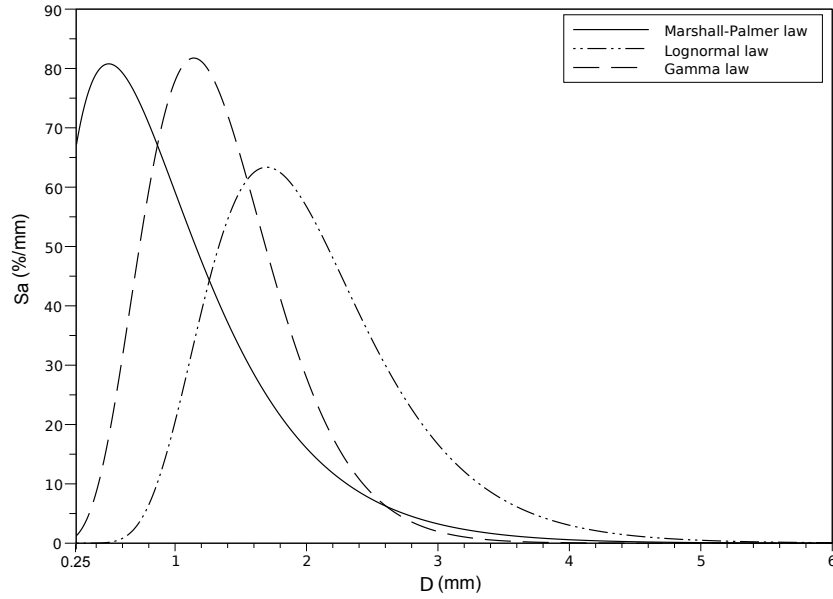
Figure 2: Percentage of drops reaching the ground on 1 m^2 per second as a function of their diameter for the three raindrop size distribution laws and a rainfall intensity of 50 mm h^{-1}.
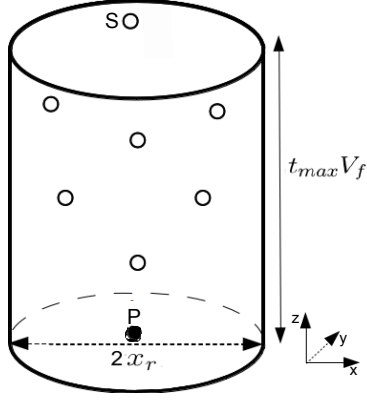
Figure 3: Volume of influence ω_i of a fixed secondary drops (S) with terminal velocity V_f. A fixed primary drop (P) disturbs an area of radius x_r.
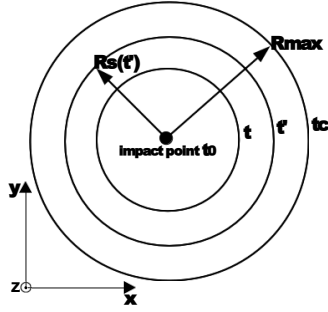
Figure 4: Spreading of the perturbation created by the impact of a raindrop in the horizontal plane.
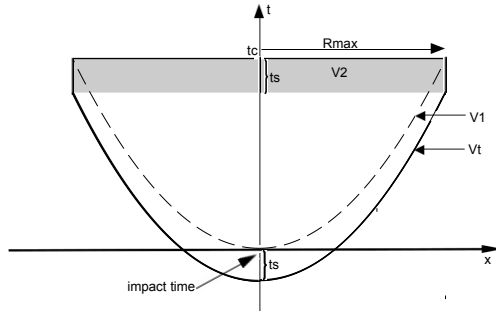
Figure 5: Spreading of the perturbation created by the impact of a raindrop in the time-space coordinates where V_1 is drawn with a dashed line, V_2 is in gray color and V_t is drawn with a solid line.
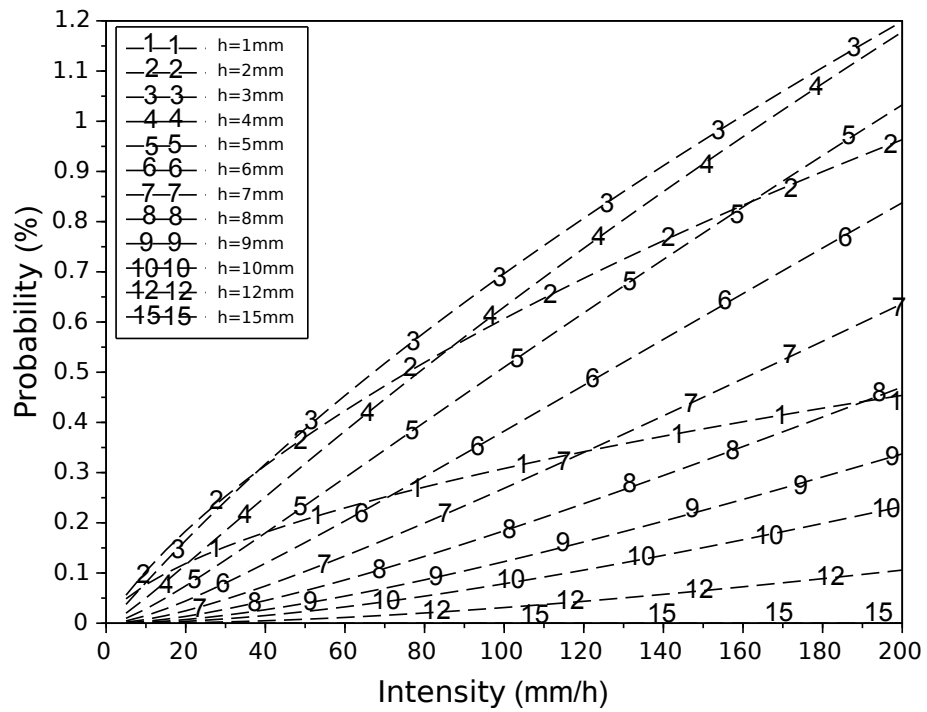
Figure 6: Total probability of shear interaction as a function of rainfall intensity and water layer depth for the Marshall-Palmer law.
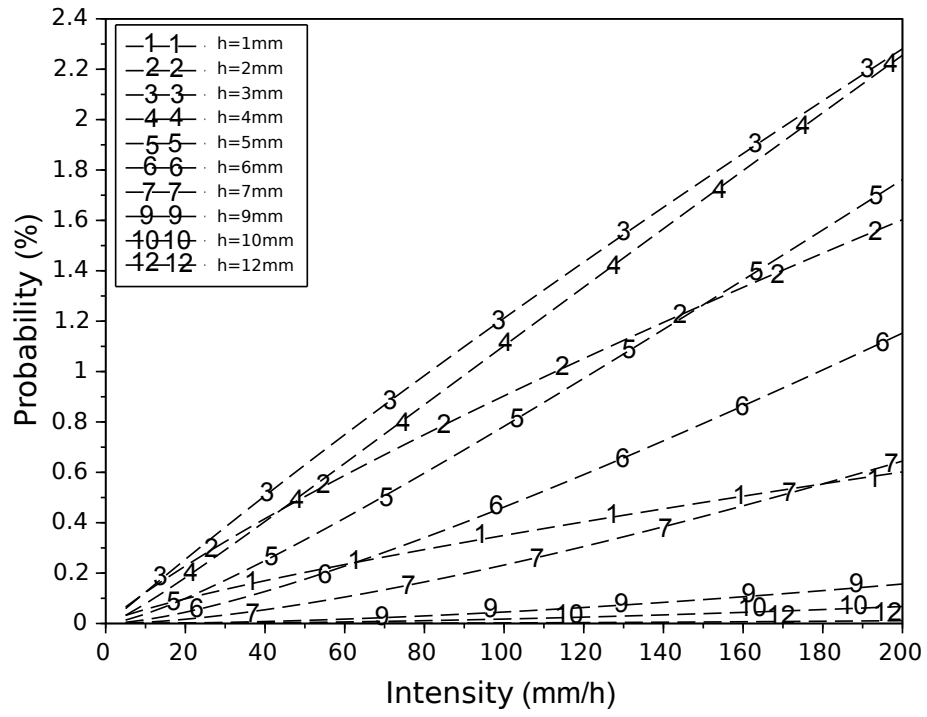
Figure 7: Total probability of shear interaction as a function of rainfall intensity and water layer depth for the Gamma law.
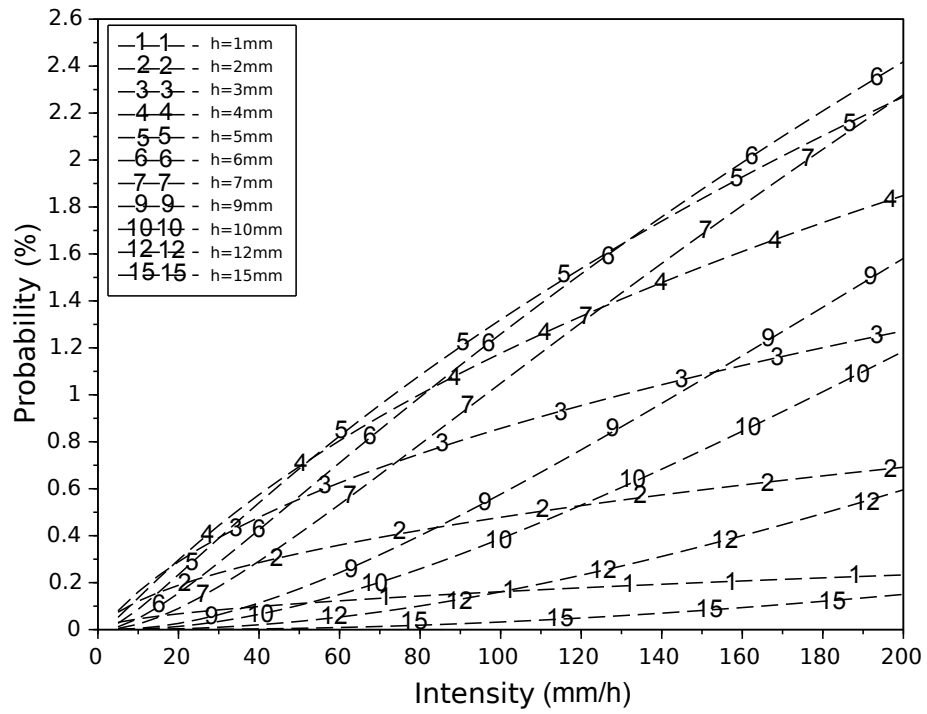
Figure 8: Total probability of shear interaction as a function of rainfall intensity and water layer depth for the Lognormal law.
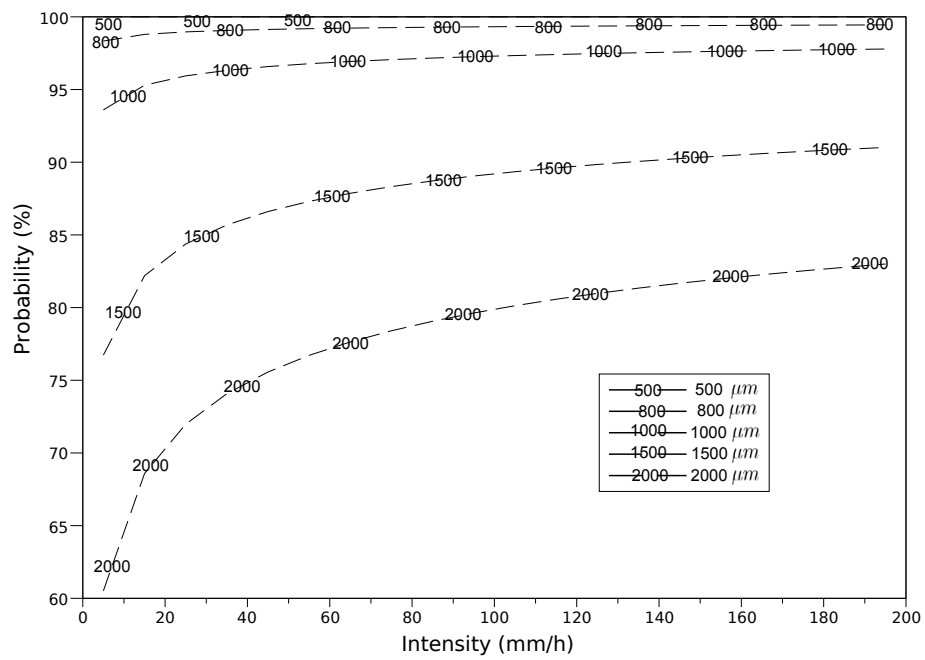
Figure 9: Rainfall interaction with settling particles as a function of rainfall intensity for several particles classes with $c = 10$ g L^{-1} and $h = 3$ mm using the Marshall-Palmer law.
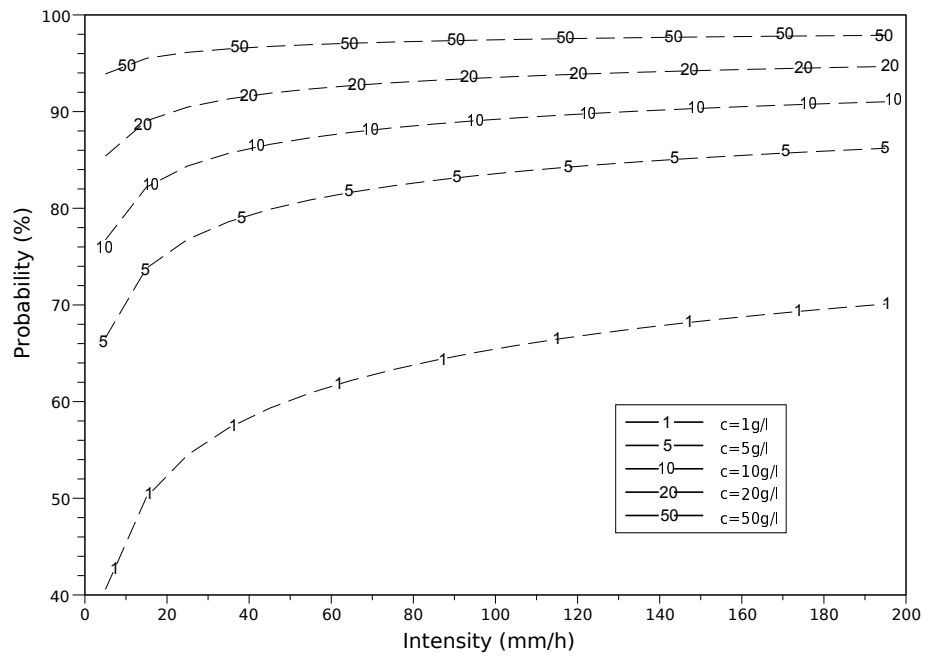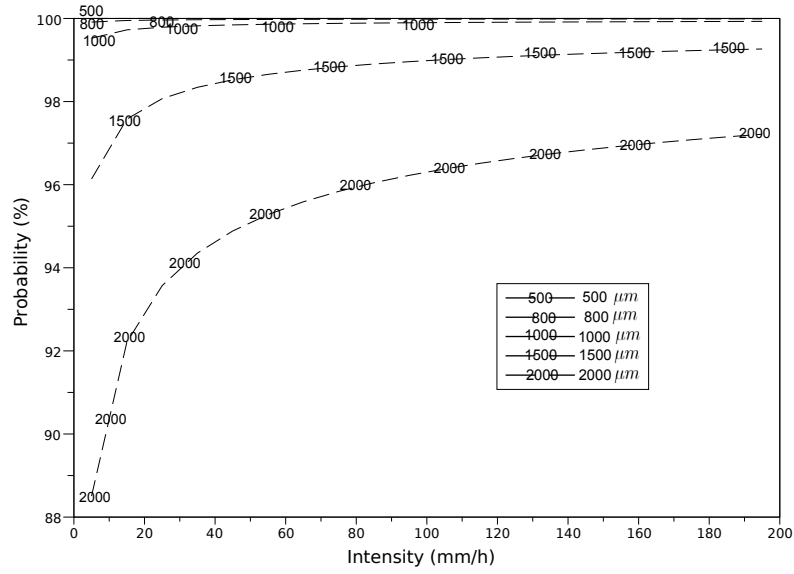
Figure 10: Rainfall interaction with settling particles as a function of rainfall intensity for several concentrations of particles of size 1500 μm and $h = 3$ mm using the Marshall-Palmer law.
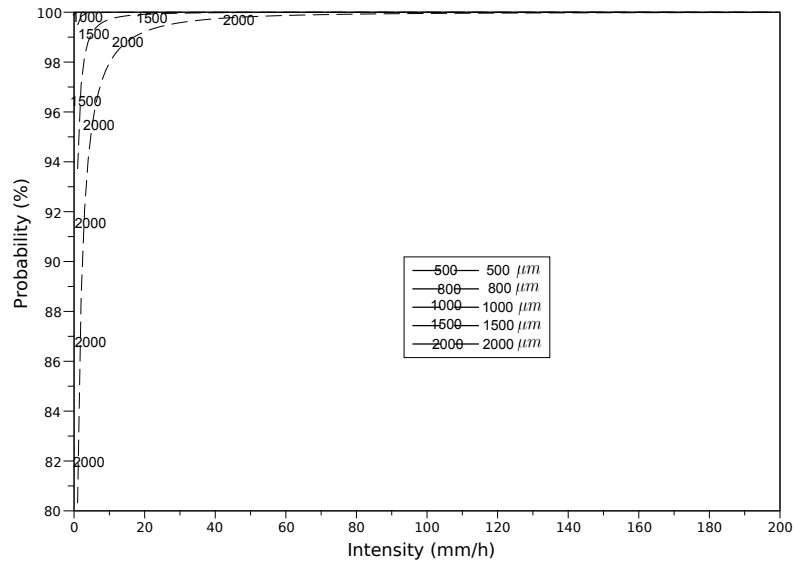
Figure 11: Rainfall interaction with settling particles as a function of rainfall intensity for several particle classes with $c = 10$ g L^{-1} and $h = 3$ mm using the Gamma law.

Figure 12: Rainfall interaction with settling particles as a function of rainfall intensity for several particle classes with $c = 10$ g L^{-1} and $h = 3$ mm using the Lognormal law.