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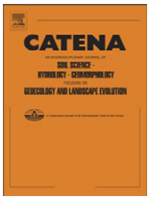

Soil detachment caused by divided rain power from raindrop parts splashed downward on a sloping surface

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In modelling interrill erosion caused by raindrops splashed on the soil surface, the parameters most frequently considered are the kinetic energy of the raindrops, the rain power and the rainfall intensity. The present paper presents arguments supporting the inclusion among these parameters of that part of the raindrops' kinetic energy that is expended to splash the soil downslope and introduces a theoretical mathematical equation for a dimensionless function of the kinetic energy distribution f_d. The f_d function depends on the raindrop angle of incidence θ and is derived from an appropriate division of a falling raindrop into two parts. The multiplication product of the dimensionless function f_d and the rain power R (W m^{-2}) yields the *divided rain power* R_d (W m^{-2}). An experiment on loess soil with simulated rainfall at intensities of 19, 33 and 54 mm h^{-1} and slopes of 4%, 12% and 25% allowed measurement not only of the soil particle detachment rate ψ (g m^{-2} s^{-1}) caused by surface runoff but also the values of soil splash determined in three directions (upslope, downslope and lateral to the direction of the soil slope). The data obtained were used to estimate α and β coefficients of the power function ($\psi = \alpha R^{\beta}$ and $\psi = \alpha R_d^{\beta}$) that links the soil particle detachment rate (ψ) caused by surface runoff with the rain power (R) and with the divided rain power (R_d). The determination coefficients R^2 were 0.52 and 0.64, respectively. The use of the R_d improved the correlation with the soil particle detachment rate ψ because of the standardisation of trends over a wide range of input values. Additionally, two 3-factor multiple regression analyses were conducted using a main-effect model. Apart from initial soil moisture and density, the predictors R or R_d were used, and the determination coefficients R^2 were 0.49 and 0.64, respectively. The results demonstrated the benefit of using the dimensionless function of the kinetic energy distribution f_d in empirical models of interrill erosion caused by raindrops.

1. Introduction

The impact of raindrops on a soil surface that leads to detachment (splash) has been known and mathematically described for over half a century (Ellison, 1944; Rose, 1960). Modelling soil particle detachment due to rainfall allows for improved prediction of soil losses; therefore, many modern erosion models (e.g., WEPP, EUROSEM or LISEM) include a module describing erosion directly caused by raindrops (Ascough et al., 1997; De Roo et al., 1996; Morgan et al., 1998). Rainfall intensity and its kinetic energy are common estimators that define the ability of raindrops to detach soil particles (Hammad et al., 2006; Morgan et al., 1998; Watson and Laflen, 1986). Typically, empirical models of soil erosion represent surface erosion as a power function of the rainfall intensity or rainfall kinetic energy with constants that depend on soil characteristics and estimations from experimental data as follows:

$$D_i = aI^b, \tag{1}$$

where D_i is the interrill erosion rate (kg m^{-2} s^{-1}), I is the intensity of rain (m s^{-1}), and a and b are the regression coefficients (Meyer, 1981). To expand the usability of these models for soil surfaces of different slopes, the so-called slope factor, which does not depend on the soil characteristics, condition of the surface layer or erosion processes, is used (Meyer and Harmon, 1987; Zhang et al., 1998). The slope factor S_f is related to the transport ability of overland flow and is a function of the eroded hillslope angle:

$$S_f = 1.05 - 0.85\exp(-4\sin\theta), \tag{2}$$

where θ is the slope gradient (degree) (Liebenow et al., 1990). The interrill erosion rate D_i is, in turn, related to the slope factor S_f as follows:

$$D_i = K_i I^b S_f, \tag{3}$$

where K_i is the coefficient of interrill erodibility of soil (kg s m^{-4}). The commonly used rainfall intensity or rainfall kinetic energy is calculated using the full volumes of the raindrops and their terminal velocity on impact with the soil surface but ignores the energy that transfers to

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the soil particles and causes their detachment and ejection in an upslope or downslope direction from the eroding surface.

A raindrop hitting the soil surface splashes, and a significant part of the raindrop volume is ejected sideways in the form of droplets of different sizes, accompanied by soil particles. Coarse soil grains of 50 to 2000 μm are ejected as individual grains, whereas multiple smaller grains <50 μm are transported within the drops of a splash (Leguédois et al., 2005). The horizontal and vertical splash distances largely depend on the terminal velocity that a raindrop has at the moment of impact, the size of the raindrop, the slope and microrelief of the eroded surface and the size of the soil grains (Legout et al., 2005). The ground surface density (scarified or crusted soil) and moisture (air-dry or water-saturated soil) are important factors that affect soil splash both qualitatively and quantitatively. During rainfall, the soil may become fully saturated with moisture, which inhibits infiltration and facilitates the appearance of water (ponding water or an overland flow) on the soil surface. This surface water stops the detachment of soil particles completely after reaching a threshold depth (i.e., 2–3 diameters of a raindrop) (Brodowski, 2010; Gao et al., 2003). In addition, results achieved by Torri et al. (1987) indicate that the soil particle detachment rate (within the range of water layer depths from 0.2 to 2.0 mm) exponentially decreases and drops almost to zero for a water layer depth from 1.6 to 2.0 mm. Palmer (1963) researched the influence of the water layer on the raindrop hitting force and reported that the impact force measured under the water layer increases with depth to a maximum at some critical depth beyond which the impact force decreases to zero. Similarly, the maximum weight of the soil splash was recorded at the same critical depth of the water, which depended on the droplet size and amounted to 2, 4, and 6 mm, respectively, for droplets with diameters of 2.9, 4.7, and 5.9 mm that fell from a height of 1.52 m. This research revealed that a thin water layer can even enhance the droplet impact force and contribute to a larger soil splash than occurs when no stagnating or flowing water is present (Palmer, 1963). An intensification of the erosion processes can also be observed when the soil cohesion is low, which can result from little clay within the soil or the wetting of an air-dry soil (Torri et al., 1987).

The value of the vertical pressure exerted by raindrops impacting a horizontal soil surface depends on the distance from the impact centre (Nearing et al., 1987). For a 5.6 mm diameter droplet falling straight down from a 14 m height, the maximum impact pressure was recorded at 1.8 to 2.3 mm distant from the impact centre and ranged from 190 to 290 kPa. These values recorded on the soil surface are two orders lower than the pressures exerted on a rigid surface (Nearing et al., 1987). The reason for the lower vertical pressure of impact on the soil may be the granularity of the soil and a shear stress on its surface that expends part of the kinetic energy of the droplet. The transfer of the kinetic energy of raindrops to a soil surface causes the decomposition of soil aggregates and the ejection of soil particles in different directions around the impact centre. The raindrop impact and the transport of the fragmented soil particles up to a few millimetres (2–3 mm) inside the soil profile causes the deposition of the particles in the soil pores and, thus, the thickening of the surface soil layer and the formation of a surface crust. The density of the surface crust depends on the soil composition and may reach up to 1.91 g cm^{-3} (Roth, 1997). Because of its increased shear strength, the surface crust significantly increases the amount of energy that is necessary to detach soil particles and initiate water erosion (Brodowski, 2009). The splash direction provides information concerning the directions of the momentum transfer from the raindrops to the soil particles. After a vertical fall of a raindrop onto a horizontal soil surface, the dispersion of the soil particles by the splash drops occurs symmetrically; however, with an increase of the soil slope, an increasingly asymmetric dispersion develops downslope (Furbish et al., 2007; Ghadiri and Payne, 1988). By using simulated rainfalls, it was observed that the number of detached particles is the same on horizontal and sloped surfaces (Ghadiri and Payne, 1988). However, the total displaced mass increases with an increase in the slope angle, which demonstrates a higher efficiency of kinetic energy use for detaching soil particles at steeper soil surface inclinations (Fu et al., 2011).

The present work discusses a physics-based conception of using the kinetic energy from the part of the raindrop that splashes in the downslope direction, i.e., in accordance with the slope of the eroded surface, in empirical models of interrill erosion. Additionally, the results of the theoretical discussion were verified using data from laboratory tests conducted on loess soil within a rainfall simulator.

2. Derivation of the formula for divided rain power

Research into interrill soil erosion concerns the following two topics: the soil erosion (soil splash) and the kinetic energy (or momentum) of the full volume of a raindrop. A similar approach was proposed by Gabet and Dunne (2003) in a mathematical equation for the rain power. The rain power (R, W m^{-2}), which links the input of the kinetic energy from the raindrops that land vertically on the soil surface with the soil particle detachment rate, is influenced by the rain intensity (I, m s^{-1}), the slope of the eroded surface (θ, degrees) and the vegetation cover (C_v, values from 0 to 1) as follows:

$$R = \frac{\mathrm{d}E'_k}{\mathrm{d}t} = \frac{\rho I v^2 (1 - C_\mathrm{V})\cos\theta}{2}, \tag{4}$$

where ρ is the water density (1000 kg m^{-3}) and v is the terminal velocity of a raindrop. The expression E'_k is the effective kinetic energy of the raindrops, which corresponds to the unit of area and accounts for the vegetation cover of the soil surface because the growing plants or postharvest remains protect the soil surface from the destructive effect of the raindrops and reduce the direct effect of the raindrops' energy on soil particle detachment:

$$E'_\mathrm{k} = \frac{\rho I t v^2 (1 - C_\mathrm{v})\ \cos\theta}{2}, \tag{5}$$

where t is the time of rainfall(s). In the above Eqs. (4) and (5), the rain intensity on a sloped soil surface is corrected using ($I\cos\theta$). Consequently, with increased slope, the rain power (Eq. (4)) decreases due to decreasing rain flux ($I\cos\theta$). Finally, using Eq. (6) and contrasting the values of the rain power R (W m^{-2}) with the measured soil particle detachment rate ψ (g m^{-2} s^{-1}) to calculate the constants α and β, one may notice that lower values of the rain power R (resulting entirely from the increased slope angle of the eroded surface) correspond to higher soil particle detachment rates ψ. One may mistakenly conclude that decreasing rain power (by increasing the slope angle) results in higher soil particle detachment rates.

$$\psi = \alpha\ R^\beta A\left(\bar{h}, d\right), \tag{6}$$

where α and β are experimentally defined constants. The term $A\left(\bar{h}, d\right)$ is a dimensionless reduction function, which accounts for the role of flowing or ponding water of depth (h) in protecting the soil surface from the impact of raindrops of diameter (d). Analogously, when applying the formula for interrill erosion (1) proposed by Meyer (1981), a conclusion that decreased rainfall intensity (which results from the $I\cos\theta$ correction) corresponds to greater soil erosion may also be incorrect.

Soil splash is a frequently used measure of the raindrop impact on an eroded surface (Furbish et al., 2007). The research on the splash direction for various slopes of soil surface show that with an increase in the slope angle, the amount of soil detached increases downslope and decreases upslope (Fu et al., 2011). Most frequently, the increase in the downslope splash does not occur exclusively at the expense of the upslope splash because the total mass of soil detached in all directions increases with increased slope (Fu et al., 2011). Generally, an increase in