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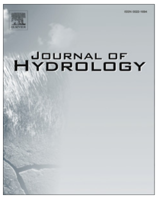

Momentum or kinetic energy – How do substrate properties influence the calculation of rainfall erosivity?

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SUMMARY

Rainfall erosivity is a key component in soil erosion by water. While kinetic energy and momentum are used to describe the erosivity of rainfall, and both are derived from mass and velocity of raindrops, it is not clear how different substrates transform this energy. In our study we conducted rainfall simulation experiments to determine splash detachment amounts of five substrates (coarse sand, medium sand, fine sand, PE balls, silt) for seven different rainfall intensities (52–116 mm h^{-1}). We used linear mixed-effect modeling (LME) to calculate erosivity predictors for each substrate. Additionally, we separated drop-size-velocity relationship into lower left and upper right quarter to investigate the effect of small and slow just as big and fast raindrops on splash detachment amounts.

We suggest using momentum divided by drop diameter as a substrate-independent erosivity predictor. To consider different substrates specific erosivity parameters are needed. Heavier substrates like sand are best described by kinetic energy multiplied by diameter whereas lighter substrates like silt point to momentum divided by diameter to the power of 1.5. Furthermore, our results show that substrates are differently affected by the size and velocity of drops. While splash detachment of light substances can be reliably predicted by drop size and velocity for small and slow drops, drop size and velocity loses its predictive power in heavier substrates like sand.

1. Introduction

The relationship between splash detachment of soil and rainfall characteristics has been in focus of research for over 60 years. Starting with Ellison (1947a), who regarded raindrop impact as dominant factor in water erosion and splash detachment of soil, several authors confirmed his findings and widened his results to a more precise link to rainfall parameters (Kinnell, 1973; Lal, 1976, 1998; Riezebos and Epema, 1985). Therefore, the erosivity of rainfall is mainly driven by intensity, drop size distribution (DSD) and terminal velocity of raindrops when hitting the soil surface. Additionally, inherent soil properties like texture and structure stability influence splash detachment (Bradford et al., 1987; Ellison, 1947b; Poesen and Savat, 1981; Quansah, 1981). For example, grain-size distribution has to be taken into account to improve the definition of soil detachability by raindrop impact (Torri et al., 1987).

The erosivity of rainfall can have an important influence on ecosystems through the initiation of soil erosion and is related to changes in climate (Elagib, 2011; Diodato and Bellocchi, 2009). Rainfall erosivity can increase in forest ecosystems compared to open field (Geißler et al., 2012; Nanko et al., 2004) and threaten their services and functions. In less dense ecosystems, rainfall erosivity can influence seed germination and sapling success e.g. during afforestation (Cerdà and Garcıa-Fayos, 2002; Wang et al., 2012). Contrary, decreasing rainfall erosivity due to changes in climate can lower land degradation. On the other hand, increasing extreme seasonality of rainfall in semiarid lands can lead to high runoff and erosivity (Elagib, 2011).

In soil erosion modeling, soil loss by water erosion is related to rainfall by different precipitation properties. The Revised Universal

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Soil Loss Equation (RUSLE) includes R as the rainfall and runoff factor (Renard et al., 1997). The R factor gives information on how rain energy and intensity contribute to soil loss, using the rainfall erosivity index (EI). Other physically based models like the Water Erosion Prediction Project (WEPP) use rainfall amount, normalized peak intensity and time to peak intensity as input for rainfall erosivity (Demény et al., 2010).

Rainfall intensity and drop size contribute to soil loss in a way that smaller drops are less efficient for soil detachment with low rainfall intensities (Sharma and Gupta, 1989) and soil is more likely to be detached with higher rainfall intensities (Sloneker et al., 1976). Rainfall intensity only calculated by mean intensity and drop diameter rather than the complete DSD overestimates kinetic energy for low intensities and underestimates it for higher ones (Assouline, 2009). Underestimation of rainfall erosivity can also occur when comparing natural conditions to the prediction by the Universal Soil Loss Equation (van Dijk et al., 2002). However, decreasing rainfall intensities cannot always be linked to decreasing rain drop size and rain drop speed. Carter et al. (1974) measured decreasing drop diameter with increasing rainfall intensity above 50 mm h^{-1}. Whereas Assouline (2009) found a threshold at 100 mm h^{-1}, Abd Elbasit et al. (2010) found this threshold at 20 mm h^{-1} and showed a decreasing kinetic energy with increasing rainfall intensity. Further, these studies point out that the relation between rainfall intensity and drop size and drop velocity is often non-linear. Therefore, more insight is needed how the drop-size-velocity relationship (DSVR) affects splash detachment.

Drop mass and drop velocity describe the kinetic energy (*KE*) and momentum (*M*) of a rain drop. Kinetic energy is calculated as $KE = \frac{m \times v^2}{2}$ and momentum as $M = m \times v$ (where m = rain drop mass and v = rain drop velocity). Some studies indicate that *KE* is not describing raindrop erosivity reliably (Ghadiri and Payne, 1988) due to *KE* being not a constant proportion of impact energy and suggest to better use *M* over *KE* (Rose, 1960). Other studies using rainfall simulation show that the intensity-kinetic energy relationship follows natural conditions and *KE* and *M* can both be used to predict soil splash (Abd Elbasit et al., 2010; Sanchez-Moreno et al., 2012). Another approach to determine the influence of *KE* and *M* on sediment detachment was introduced by Salles and Poesen (2000), using *M* multiplied by drop diameter to predict soil detachment.

In our study we take advantage of the similarity of the formulas deriving kinetic energy and momentum: both are related to mass and velocity, but kinetic energy as a power function with 2 as exponent and momentum as a linear relation, equivalent to an exponent of 1. Thus, quantifying the exponents of the relation between splash detachment and drop mass and velocity may help to identify whether *KE*, *M* or *M* multiplied by drop diameter are best suited for describing erosivity.

For example, if kinetic energy is higher in forest ecosystems than in open field (Nanko et al., 2004; Geißler et al., 2012) and if drops do not reach terminal velocity under forests and are therefore slower (Nanko et al., 2008; Frasson and Krajewski, 2011), kinetic energy can only be increased by heavier drops. Taking this together with the observation that rain passage through forest canopies increases drop sizes, drop mass may play a major role for rainfall erosivity especially under forest canopy. Thus, *M* rather than *KE* may be the appropriate erosivity index under forest canopy. Since *M* increases with drop diameter, the portion of large rain drops may contribute more to the prediction of erosivity than the portion of small raindrops.

Considering the relation of *KE* or *M* to soil properties for describing splash detachment, it has been shown that detachment rates are soil-type dependent (Assouline et al., 2007; Wainwright and Parsons, 2002). Contrary to that, Angulo-Martínez et al. (2012) could not detect any difference in splash detachment amounts between three different soil types (Cambisol, Gypsisol and Solonchak) and emphasized that the differences were only caused by different rainfall intensities. Supporting these findings, Salles et al. (1999) found no difference when fitting splash detachment rates of different soil types using *M* multiplied by drop diameter.

The influence of soil properties on the effect of *KE* and *M* is only roughly investigated (Al-Durrah and Bradford, 1982; Bradford et al., 1987). To analyze the influence of raindrops on splash detachment best, all studies transformed rainfall intensity into a DSVR and used one DSVR per rainfall intensity. DSVR can be turned into a mathematical formula consisting of rain drop mass and velocity exponentiated with different factors fitted to the observed soil loss (Salles and Poesen, 2000).

In this study we want to examine the influence of different substrates on splash detachment and their relationship to rain drop mass and velocity. Additionally, our objectives are to test if splash detachment is sufficiently described by one average parameter for the drop size and drop velocity relationship alone. Therefore, we divided it into specific intensities using the lower left and upper right quarter of the relationship graph. We may find distinct differences between these wide ranges.

We propose the following hypotheses:

(1) The momentum of large drops (upper right quarter) is best suited to predict substrate detachment, given that substrate diameter is considered as covariate.
(2) Fine substrates respond to the kinetic energy of small drops, while coarse substrates respond more to the momentum of large drops.
(3) Small and slow drops are more suitable to describe splash detachment amounts of light substrates whereas big and fast drops describe splash detachment amounts of heavier substrates best.

2. Materials and methods

2.1. Rainfall simulation

Our study was conducted at the Soil Physics Laboratory, Wageningen University, Netherlands. We generated rainfall using an indoor rainfall simulator with a sprinkling height of 4.0 m and a Lechler nozzle type 461.008.17 CG. To control the flow rate a regulator valve and a flow meter were used and set up to 14 L per minute. Within the nozzles' heterogeneous sprinkling behavior we could produce seven different rainfall intensities ranging from 52 mm h^{-1} to 116 mm h^{-1} on an area of 2 m^2. They were validated by three test runs of 15 min each and runs differ to a maximum of 5% error at each position. Every chosen position ensured no detached substrate splashing to the other positions (Legout et al., 2005; Leguédois et al., 2005). For measurements, we used intensities of 52, 60, 72, 80, 88, 100 and 116 mm h^{-1}. Since drop velocity decreases slightly with increasing intensity, we used inverse velocity for our calculations.

2.2. Measurement of drop-size-velocity relationship (DSVR)

We recorded the rain drop-size-velocity relationship by an optical disdrometer (Thies laser precipitation monitor, LPM) on every chosen intensity spot with two replicates (Bloemink and Lanzinger, 2005; Lanzinger et al., 2006; Salles and Poesen, 1998). From the DSVR, the distributions of drop mass and drop velocity were calculated. We derived three different distributions for each intensity:

(1) the complete spectrum (all drops),
(2) the lower left quarter (slow and small drops) and
(3) the upper right quarter (fast and big drops)