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A Comparison of Rain Erosivity Parameters for Predicting Soil Detachment on Interrills

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ABSTRACT

Interrill erosion is largely controlled by rainfall characteristics. Several rainfall parameters (e.g. rainfall intensity, kinetic energy, momentum) are being used to characterize the eroding power of the rain. There is still a lot of debate as to the performance of various erosivity parameters. This debate and confusion are due to limited sets of reliable experimental data and to a lack of understanding of fundamental processes involved in soil detachment by raindrop splash. Laboratory experiments have been conducted to study the effects of various rain properties on soil detachment due to raindrop impact. Splash cups were exposed to simulated rainfall intensities ranging between 10 and 140 mm h^{-1}. The detached sediment was collected and weighted whereas rain intensity, equivalent drop diameter and fall velocity of raindrops were measured with an optical spectro pluviometer (OSP). Statistical analysis to evaluate which rain parameter best predicts the mass of sediment detached (D_s) have been made. Linear correlation between D_s and the product of drop size (D) by drop velocity (V) i.e. $D^{\alpha}V^{\beta}$ with values of α varying between 1 to 6 and β between 0 to 2, have been computed. The experiments were conducted with two soils: a very fine sand and a silt loam. Results indicate that the coefficients of determination (R^2) for α ranging between 3 to 6 and β lower or equal to 2 best describe the experimental data. Comparison of the results for the two soils is made and the best erosivity parameter to describe soil detachment by splash is given.

INTRODUCTION

Soil loss by interrill erosion is closely linked to rain properties, partly through the detaching power of raindrops striking the soil surface and partly through the contribution of rain to runoff. Since Ellison (1952) and other researchers in the USA proposed raindrop impact as the dominant agent of water erosion, numerous authors confirmed and argued this hypothesis. Bauer (1985) pointed out that especially in Central Europe where many rains do not generate overland flow, but splash sets in already at the first drop impact, we must regard raindrop impact as an important denudational process. Many studies of splash erosion have been largely concerned with the establishment of equations relating splash detachment to rain erosivity indices (Ekern, 1950; Bisal, 1960; Rose, 1960; Bubenzer and Jones, 1971; Ghadiri and Payne, 1977; Kinnel, 1982; Gilley and Finkner, 1985; Nearing and Bradford, 1985; Sharma and Gupta, 1989 and Sharma et al., 1991).

Laboratory experiments under controlled simulated rain were conducted to investigate the effects of the rain properties on soil detachment due to raindrop impact. From detailed measurements of the rain (raindrop size and velocity) various rain erosivity parameters were determined.

The objective of this study was to test the performance of different rain erosivity parameters in order to predict soil detachment by raindrop splash on interrills under controlled rain and soil conditions. Finally, from statistical analysis, the study allowed to identify the optimal rain erosivity parameter.

METHODS OF INVESTIGATION

The splash cup technique, first introduced by Ellison (1947), was used to measure the mass of sediment detached. The method consists in collecting the splash loss from cups filled with soil material (e.g. Mazurak and Mosher, 1968; Morgan, 1978,). In this study a PVC splash cup with a diameter of 5 cm and a height of 4 cm was used (Poesen and Govers, 1986). The splash cup, which has a filter at the bottom, was filled with the two selected soils. The very fine sand has been chosen because of its very high susceptibility to detachment by raindrop splash (Poesen, 1985) and the silt loam because of its representatively of the topsoil found in Central Belgium. The physical characteristics of these two soils are given Table 1.

The soil was moistened to its water-holding capacity by placing the splash cup inside a pan, which contained water. At the beginning of the rain exposure, the surface of the soil was made flush with the rim of the splash cup.

Each splash cup was exposed to the simulated rain during periods varying between 4 min. for the highest rain

Table 1. Physical characteristics of the two tested soils.

Soil		Sand	Silt Loam
Grain size	50 to 2000 μm (%)	100	18
	2 to 50 μm (%)	-	70
	less than 2 μm (%)	-	12
	D_{50} (mm)	0.096	0.030
Dry bulk density (g cm^{-3})		1.25	1.15
grav. Moisture content (%)		37	43

*D_{50} is the median grain size. **Grain size distribution were determined using the sieve pipette method

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intensity (142 mm h^{-1}) to 15 min. for the lowest rain intensity (10 mm h^{-1}). In order to collect the ejected sediment, the splash cup was placed inside an open cylindrical container. A beaker located at the output of the container collected the splashed sediment and the water. At the end of the experimental rain, the inner wall of the container was carefully cleaned with water. The sediment was dried in an oven and subsequently weighed. The mass of detached sediment per unit of exposed soil surface and time (D_s ; g m^{-2} s^{-1}) was calculated. For each rainfall intensity, six splash cups were exposed to the simulated rain.

Rain was simulated with a downward-oriented continuous nozzle spray system comparable to the one described by Parsons et al. (1998). A sprinkler system consisting of four nozzles (Lechler axial-flow cone jet nozzles) is located at the corners of a 50 cm rectangular frame. The nozzles were positioned 4.7 m above the soil surface. The nozzles were supplied by a water tank placed 2.8 m above. Rain intensity could be varied using four electric valves, which switched individual nozzles on or off. During our experiments, the following Lechler nozzles were used: one nozzle numbered 460.788 and three nozzles numbered 460.968. We took advantage of the non-uniformity of the rainfall intensity over the sprinkled area in order to select a wide range of rainfall intensities, i.e. from 10 to 140 mm h^{-1}.

The raindrop properties were measured using an Optical Spectro Pluviometer (Hauser et al., 1984 ; Salles et al., 1998 and Salles and Poesen, 1999). This device allows the real time measurement of the diameter and the fall velocity of raindrops. Two rain samples were taken in order to characterize drop size and fall velocity distributions. A first one before the exposure of the first splash cup and the second one just after the exposure of the sixth splash cup. Diameter and velocity for each detected raindrop were stored in a file.

From the raindrop diameter (D) and the fall velocity (V), erosivity indices ($Er_{\alpha,\beta}$; expressed as a summation of power law functions of D and V) were calculated:

$$Er_{\alpha,\beta} = C_{\alpha,\beta} \sum_{n} D^{\alpha} V^{\beta} \qquad (1)$$

where α and β are integer values dependent of the rain parameter considered, n is the number of drops detected and $C_{\alpha,\beta}$ are constants such that $Er_{\alpha,\beta}$ expresses (when possible) a commonly used rain parameter.

For examples, with $\alpha = 3$ and $\beta=0$, $Er_{3,0}$ refers to the rainfall intensity suggested as a rain erosivity index by Nearing et al. (1989) and Govers (1991). $C_{3,0}$ is equal to $\pi/(6\ S\ \Delta t)$ where S is the sampling surface and Δt is the sampling time. The kinetic energy was suggested as a rain erosivity index (by e.g. Free, 1960 ; Bubenzer and Jones, 1971 ; Quansah, 1981 ; Poesen, 1985 and Morgan et al., 1998). $Er_{3,2}$ refers to kinetic energy with $C_{3,2}$ equal to $\rho\ \pi/(12\ S\ \Delta t)$ where ρ is the water density in standard conditions. Rose (1960), Park et al. (1983) and Styczen and Høgh-Schmidt (1988) reported the momentum of raindrop as an erosivity index. The momentum is expressed by $Er_{3,1}$ with $C_{3,1}$ equal to $\rho\ \pi/(6\ S\ \Delta t)$.

In order to cover all the suggested erosivity indices in the literature we will consider $Er_{\alpha,\beta}$ with α varying between 1 to 6 and β between 0 to 2. From statistical analysis a comparison of the ability of rain properties to predict mass of detached sediment by raindrop impact has been conducted. Relationships between the mass of sediment detached by splash D_s and the index $Er_{\alpha,\beta}$ were investigated and compared using linear regression. The retained criterion to compare the suitability of the index to express the ability of raindrops to detach soil was the coefficient of determination R^2.

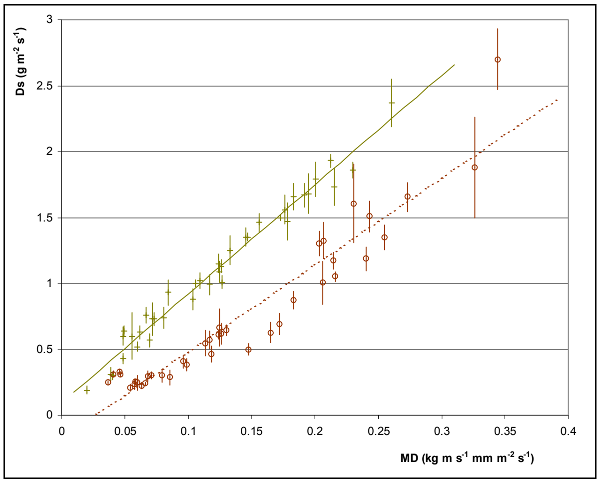

Figure 1: Scatter plot of the mass of sand (solid line) and silt loam (dashed line) detached and splashed by raindrop impact (D_s) versus the rain erosivity parameter: momentum multiplied by the drop diameter (MD). Standard deviations are illustrated by the vertical bars. Relations obtained by linear regression are also plotted

RESULTS

The R^2 values obtained for various α and β values are reported in table 2a for the experiments with the fine sand and in table 2b for the experiments with the silt loam. General comments valid for both sand and silt loam soils are as follows i) there exists a very good correlation between $Er_{\alpha,\beta}$ parameters and the mass of detached sediment (D_s). ii) The inadequacy of the parameters $Er_{1,k}$ and $Er_{2,k}$ to predict D_s whatever is the value of k. iii) Better values of R^2 are obtained as long as α is larger or equal to 3. The results confirm that the parameter that would come in mind intuitively, i.e. the mass of water, is a relevant parameter to predict soil detachment by raindrop splash. With α larger or equal to 3 and whatever is the β value, R^2 range from 0.93 to 0.98 for the sand and from 0.88 to 0.91 for the silt loam. It means that, statistically, the use of an erosivity index $Er_{\alpha,\beta}$ with α larger or equal to 3 and β varying from 0 to 2 is satisfying. Therefore, the erosivity parameters usually suggested such as rain erosivity indices, momentum ($Er_{3,1}$) (Rose, 1960), rain intensity ($Er_{3,0}$) (Smith and Wischmeier, 1957), kinetic energy ($Er_{3,2}$) (e.g. Free, 1960 and Morgan et al. 1998), momentum multiplied by drop circumference ($Er_{4,1}$) (Al-Durrah and Bradford, 1982) , KE per drop circumference ($Er_{,5,1}$) (Meyer, 1965), KE multiplied by rain intensity or the square of the raindrop momentum ($Er_{6,2}$) are statistically valid according to the retained criterion.

What distinguishes results for the silt loam soil from results for the sand is the lower correlation that exists between mass of detached sediment and $Er_{\alpha,\beta}$ indices. This is, first of all, the consequence of the higher difficulty of operating always in the same experimental conditions with the silt loam in comparison with the sand. That was

Table 2a:Coefficient of determination R^2 of the linear fit regression between the mass of detached sand (D_s) and the erosivity indices $Er_{\alpha,\beta}$. α is the exponent of diameter and β is the exponent of fall velocity.

		α values					
		1	2	3	4	5	6
β values	0	0.670	0.857	0.953	0.974	0.961	0.932
	1	0.730	0.890	0.961	0.977	0.969	0.948
	2	0.711	0.885	0.958	0.973	0.967	0.947

Table 2b: Coefficient of determination (R^2) of the linear fit regression between the mass of detached silt loam (D_s) and the erosivity indices $Er_{\alpha,\beta}$. α is the exponent of diameter and β is the exponent of fall velocity.

		α values					
		1	2	3	4	5	6
β values	0	0.522	0.758	0.879	0.911	0.907	0.894
	1	0.580	0.800	0.893	0.911	0.904	0.890
	2	0.563	0.806	0.899	0.912	0.900	0.882

already indicated by the higher standard deviation of D_s for the silt loam. Secondly, due to the composition of the silt loam, the detachment mechanisms involved with this soil and the behaviour of this soil under rain condition are more complex.

Notwithstanding the fact that the coefficients of determination are not statistically different at a 99% confidence interval, an attempt is made to select a rain erosivity index that best predicts the sediment detachment during our experiments. The best one that predicts the mass of detached sand is $Er_{4,1}$, i.e the momentum multiplied by the drop diameter and for the silt loam soil both $Er_{4,0}$, $Er_{4,1}$ and $Er_{4,2}$ are equal in predicting the mass of detached sediment. Relations between splash detachment D_s ($g\ m^{-2}\ s^{-1}$) and the index (noted MD because $Er_{4,1}$ is the raindrop momentum M multiplied by the drop diameter D) are plotted in figure 2 for both soils. The respective equations of the fitted curve are:

$$D_s = 8.29\ (MD) + 0.09 \quad \text{for the sand} \qquad (2)$$

$$D_s = 6.59\ (MD) - 0.18 \quad \text{for the silt loam} \qquad (3)$$

with D_s ($g\ m^{-2}\ s^{-1}$) and the product MD expressed in ($kg\ m\ s^{-1}\ mm$) ($m^{-2}\ s^{-1}$).

CONCLUSIONS

For a saturated fine sand and a saturated silt loam, all rain parameters of the form $Er_{\alpha,\beta}$ with α in the range 3 to 6 and β lower or equal to 2 are capable to describe soil detachment by raindrop splash (i.e momentum, kinetic energy or a combination of these indices with the drop diameter or the drop section) reasonably well. An optimum in the determination coefficient between mass of splashed sediment and the index $Er_{\alpha,\beta}$ was obtained for α equal to 4 and β equal to 1. The analysis suggests that momentum multiplied by the drop diameter (MD) is the best erosivity parameter to predict soil detachment.

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