Impact of Rainfall Microstructure on Erosivity and Splash Soil Erosion Under Simulated Rainfall

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1. Introduction

Rainfall represents the major driver of soil detachment in erosion processes. The potential of rainfall to detach soil has been defined as rainfall erosivity. The relationship between rainfall intensity and rainfall drop size distribution (DSD) controls various rainfall characteristics including the rainfall erosivity (Abd Elbasit et al., 2010). The relationship between rainfall intensity and rainfall erosivity differs due to geographical location under natural rainfall (Hudson 1965; Wischmeier and Smith, 1978; Zanchi and Torri, 1980; Van Dijk et al., 2002) and due to type and configuration of rainfall simulators under simulated rainfall (Hall, 1970; Olayemi and Yadav, 1983; Auerswald et al., 1992; Salles and Poesen, 2000). The role of rainfall microstructure on the determination of rainfall erosivity has attracted several researchers in the past. However, our understanding on this subject is still limited due to the lack of equipments that are able to measure the rainfall drop parameters and ultimately the rainfall kinetic energy. Several indices have been suggested to quantify the rainfall erosivity (Abd Elbasit et al., 2010). Generally, the suitable erosivity index must include the drop mass and velocity as major variables for raindrop power determination. The erosivity index has been described by Epema and Riezebos, 1983 as follows:

$$E \propto m^{\alpha} \, v^{\beta} \tag{1}$$

where m is drop mass in (kg); v is fall-velocity (m s^{-1}); α and β are coefficients.
The most used indices are raindrop kinetic energy (KE) and momentum (M). In the KE and M the α is equal to one where the β is equal to two in KE and one in M. In general, the raindrop fall velocity can be related to drop size by a power relationship. Accordingly, the raindrop size distribution affect both constituents of rainfall erosivity. Thus, theoretically the rainfall DSD (or rainfall micro-structure) has a great impact on rainfall erosivity. In this study, the impact of rainfall microstructure on rainfall erosivity and splash soil erosion

under simulated rainfall condition will be discussed. A dripper-type rainfall simulator located at the Arid Land Research Center, Tottori University, Japan has been used to simulate events with rainfall intensity ranged between 10 to 30 mm h^{-1}. The splash soil erosion has been evaluated using splash cup method. The rainfall kinetic energy and drop size distribution have been measured using piezoelectric sensor.

1.1 Rainfall erosivity evaluation

R- factor in the Universal Soil Loss Equation (USLE) and its revised and modified versions represents the major rainfall erosivity, which can be defined as the product of total kinetic energy of storm times its 30 min maximum intensity(EI_{30}) and annual average can be calculated as follow:

$$R - factor = \frac{1}{n}\sum_{i=1}^{n}\left[\sum_{k=1}^{m} KE\left(I_{30}\right)_k\right]_j \quad (2)$$

R-factor is average annual rainfall and runoff erosivity (MJ mm ha^{-1} h^{-1} $year^{-1}$); KE is total kinetic energy of single storm (MJ ha^{-1}); I_{30} is the maximum 30 min rainfall intensity (mm h^{-1}); m is the number of k erosive storms in each j year; n is the number of years used to obtain average R (Renard and Freimund, 1994). Several I-KE relationships can be applied in order to determine the storm kinetic energy depending on the geographical location and dominant type of rainfall. For example:

$$KE = (11.89 + 8.73 \log_{10} I) \times I \quad (2a)$$

(Wischmeier and Smith, 1958), USA

$$KE = 29.86(I - 4.29) \quad (2b)$$

(Hudson, 1965), Zimbabwe

$$KE = 36.8I(1 - 0.691e^{-0.038I}) \quad (2c)$$

(Jayawardena and Rezaur, 2000a), Hong Kong
where KE is rainfall time-specific kinetic energy (KE_{time}) in J m^{-2} h^{-1}.
Determination of the I-KE relationships under certain geographical location or simulated rainfall requires information about the rainfall KE or at least the rainfall DSD.

1.2 Raindrop erosivity evaluation

Rainfall drop size distribution (DSD) represents the primary rainfall data that can be used in order to quantify the rainfall erosivity. However, devices for continuous determination of the KE and DSD during rainfall event have been used in few meteorological stations. For this reason, several indices have been suggested to estimate the rainfall erosivity from common rainfall parameters (rainfall macro-structure), such as daily, and monthly rainfall data. Raindrop erosivity can be determine directly by using piezoelectric transducer where the measured water drop kinetic energy or momentum related with output voltage from the transducer due to the drop impact (Madden et al., 1998; Jayawardena and Rezaur, 2000b; Abd Elbasit et al., 2007; Abd Elbasit et al., 2010; Abd Elbasit et al., 2011). Anologously, optical methods have, also been utilized, where raindrop size and velocity are monitored simultaneously and then the erosivity indices are calculated directly from these two parameters (Salles and Poesen, 2000; Nanko et al., 2004). The raindrop erosivity can be evaluated from the rainfall DSD measured by different methods (continuous, disdrometers or non-continuous, filter paper and flour-pellet) and use of drop fall velocity values derived from empirical and physical relationships.

1.3 Rainfall simulation

Rainfall simulators are developed to mimic natural rainfall in its different characteristics. The rainfall properties including rainfall intensity and energy are the important parameters for determining the rainfall erosivity. Generally, rainfall simulators can be divided in two categories: single drop simulators (SDS) and multiple drop simulators (MDS). The SDS have been used intensively to investigate the splash erosion processes (e.g. Al-Durrah and Bradford, 1982; Cruse and Francis, 1984; Gantzer et al., 1985; Nearing and Bradford, 1985; Bradford et al., 1986; Nearing et al., 1986; Sharma and Gupta, 1989; Mouzai and Bouhadef, 2003; Furbish et al., 2007). Although these studies have improved our understanding for splash soil erosion, they fail to extrapolate these results to natural field condition (Abd Elbasit et al., 2010). The MDS produced range of raindrops similar to that found under natural rainfall. However, the big challenge for these simulators is to generate rainfall similar to natural rainfall or at least with I-KE trend similar to natural rainfall. The MDS can be categorized into three main groups: the drip-screen type (dripper type, dripolator), vertical spray type or nozzle-type and sprinkler or rotating spray-types. In this study, a dripper-type rainfall simulator has been used to simulate rainfall with different intensities.

1.4 Dripper-type rainfall simulators

A dripper type rainfall simulator located at the Arid Land Research Center, Tottori University, Japan was used to simulate rainfall with intensities ranging between 10 to 30 mm h^{-1} (Figure 1). The simulator is 12 m in height, which is theoretically enough for most of the drop sizes to reach their terminal velocity (Wang and Pruppacher, 1977) experimental results. The simulator consisted of a main steel frame, a dripper system, a positive displacement pump, a set of solenoid water valves to control water flow, and a computerized control system for various operations. The height of the main frame was 12.5 m and the dripper system was fixed on the top of this frame (Figure 1). The dripper system consisted of 16 disc-type water distributors attached to a horizontal steel frame (2.55 x 1.5 m) in six rows (Abd Elbasit et al., 2010). Each distributor had 45 tubes with inner and outer diameters of 2 and 3.5 mm respectively and at the end of each tube, a flat cut hypodermic needle was fixed (Figure 1). The inner and outer diameter of the needles was 0.4 and 0.6 mm respectively. The other end of the needle was attached to a metallic plate in such a way that the needle protruded 2.6 cm (Abd Elbasit et al., 2010). There were 18 metallic plates in total and each plate had two rows of needles. The distance between the rows was 6 cm, and the needles were arranged in 6 cm offset pattern with a needle to needle distance of 6 cm within the row. Under the needles, an oscillating screen was fixed in order to distribute the rainfall evenly, improve the drop size distribution and to prevent continuous water flow (Figure 3). The oscillating screen (2.35 x 1.33 m) consisted of two sheets of metallic mesh (10 mm) moving horizontally and in opposite directions of each other, driven by an electric motor (Abd Elbasit et al., 2010).

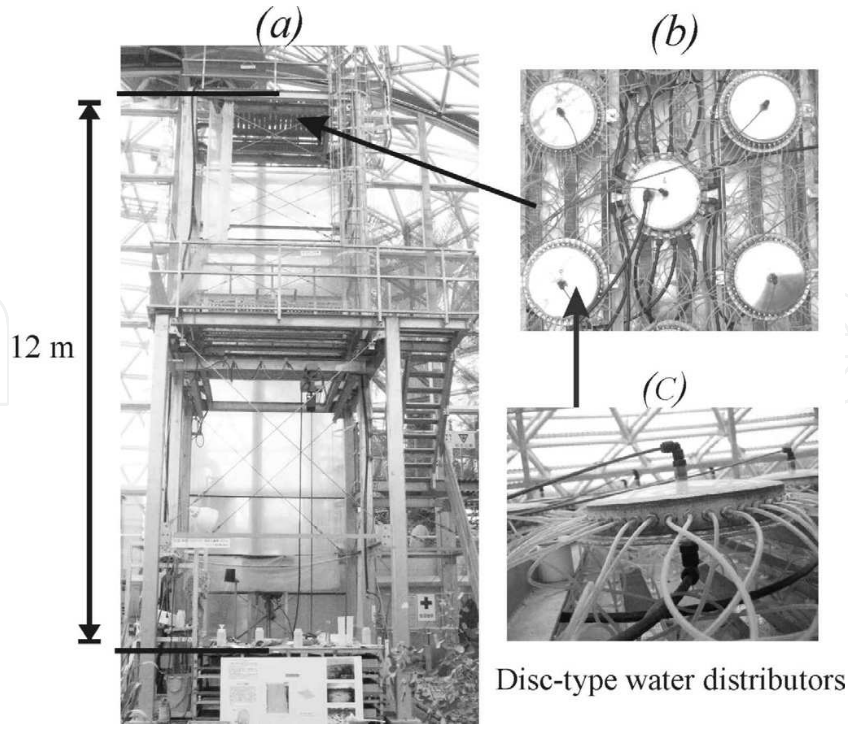

Fig. 1. Dripper-type rainfall simulator. (a) main frame, (b) dripper system, and (c) disc-type water distributor

The water pump used to supply water to the dripper system of the rainfall simulator was a positive displacement type. The water flow rate was controlled by adjusting the rotational speed of the pump (Abd Elbasit et al., 2010). The rainfall simulator was equipped with four 1 m^3 water tanks and the water flow in and out these tanks was controlled by the solenoid water valves. A high-performance water filtering system was connected to the water supply flowing to the tanks to avoid needle clogging. A computer system controlled the solenoid water valves, pump rotational speed, and oscillating screen. Before using the rainfall simulator for experiments, a priming system was used to remove all the air from the pipe system. The rainfall simulator was calibrated for the rainfall spatial distribution on the experimental area (2.1 x 1.1 m), and to determine the relationship between the flow rate and rainfall intensity (Abd Elbasit et al., 2008). In the experimental area, a table was placed at a height of 0.5 m on which the soil was placed when the splash experiment was conducted. The rainfall simulator was able to simulate rainfall intensities ranging from 1.0-200 mm h^{-1}.

2. Materials and methods

2.1 Application of piezoelectric transducer in erosivity quantification

The rainfall erosivity was measured using two piezoelectric sensors, one to measure the kinetic energy (KE, mJ) and the other to measure drop size distribution (DSD, mm), at 10 second interval. The both sensors were modified from the piezoelectric Vaisala RAINCAP® rain sensor. The measurement principle of the sensor is based on the acoustic detection of individual raindrop impact (Salmi and Ikonen, 2005). The drop impact generates acoustic waves to the piezoelectric detector (Figure 2). Resulting mechanical stresses in the piezoelectric material causes a voltage between the sensor electrodes. Due to the well known dependence between terminal velocity and mass of the drop, the drop size can be determined from the voltage signal (Abd Elbasit et al., 2010).

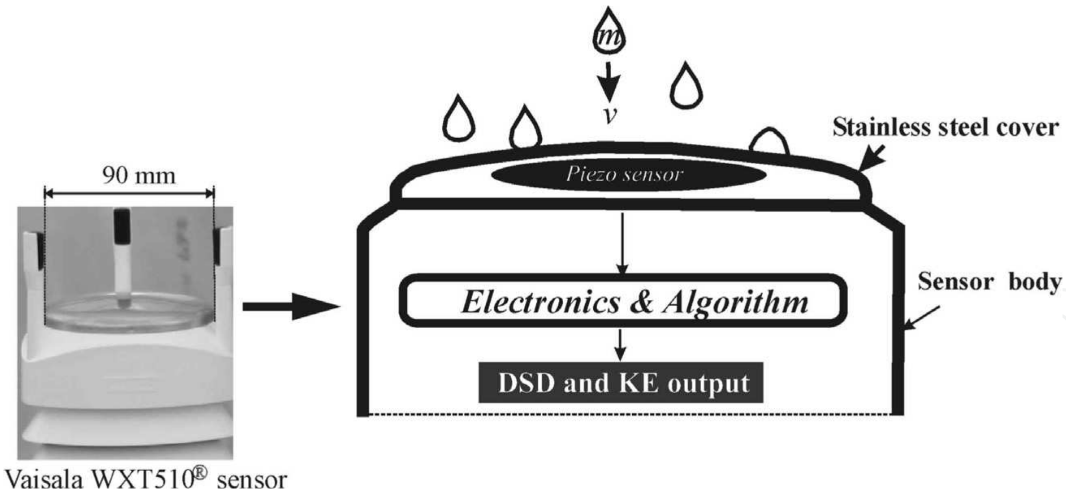

Fig. 2. Schematic view for the piezoelectric kinetic energy and drop size distribution sensors modified from Vaisala WXT510® sensor.

The sensor is constructed from a piezoelectric detector covered by stainless steel shell (Figure 2). The voltage pulses delivered by the piezoelectric element are filtered, amplified, digitized, and finally analyzed as to their selected parameters related to the raindrop size. Final computations are performed by the micro-processor system (Abd Elbasit et al., 2010). The DSD sensor was calibrated at Vaisala Rain Laboratory; Finland using controlled drop sizes falling from a height of 14 m and the velocity of each drop size was measured using two parallel laser beams and a prism. The received optical signal was converted to a voltage signal, which was proportional to the area of the laser beam intercepted by the raindrops (Salmi and Elomaa, 2007). The sensor was compared with a Joss-Waldvogel RD-69 disdrometer under natural rainfall conditions in Finland (Pohjola et al., 2008) and the results of the two methods showed significant agreement for raindrop size greater than 0.80 mm. The KE sensor was calibrated using rain drops with known kinetic energy values. The simulator and optical method used for the DSD sensor calibration were also used to calibrate the KE sensor. The raindrops' KE that was used for the KE sensor calibration was calculated from the raindrop size (controlled by the rainfall simulator) and fall velocity (measured using the optical method). The KE sensor was also validated under simulated rainfall and the sensor output (direct KE measurement) was compared with the calculated KE using rainfall DSD and empirically calculated velocity from drop size. The correlation between directly measured KE using the KE sensor and estimated KE was statistically highly significant under different rainfall intensities and empirical relationships (Abd Elbasit et al., 2007, Abd Elbasit et al., 2011). Moreover, there was agreement between the two methods in terms of the shape of the relationship between rainfall intensity and measured and estimated KE. The signals from the two sensors were logged in two notebook computers using the RS-232 serial interface and data logging software. The rainfall intensity was measured using a tipping-bucket rain gauge (Davis rain collector II, CA, USA) with 0.2-mm resolution. The rain gauge was attached to event data logger (HOBO Event Logger; Onset Computer Corp., MA, USA) with 0.5 s interval recording accuracy.

2.2 Measurement of splash soil erosion

The splash measurement was repeated three times for each rainfall intensity level. In each study three splash cups were used. The mean value for each intensity was used for determining the impact of rainfall micro-structure on soil splash erosion. The splash-cups were prepared using PVC pipe-connectors with a diameter of 10 cm and height of 20 cm (Figure 3). At a height of 10 cm, a metal screen was fixed in the cup using silicon sealant (Abd Elbasit et al., 2010). A filter paper was placed on top of the screen and then the cup was filled up to the edge with silty clay loam soil collected from the Tohaku area, Tottori Prefecture, Japan. The fine sand, silt and clay percentage was 8.24, 61.78, and 29.98%, respectively.

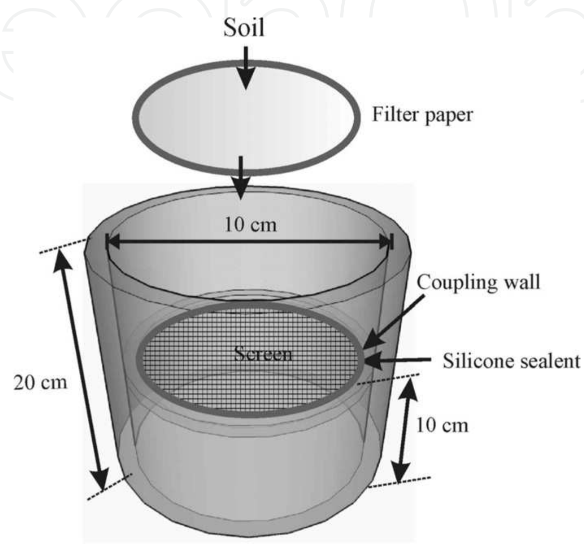

Fig. 3. Schematic view of splash cup.

The soil was air dried in a glasshouse and then mechanically crushed and sieved through 2 mm mesh. Before starting the experiment, the soil was again dried in an oven at 105 ºC for 24 hours. The bulk density of the soil in the cup was 1.10 ± 0.01 g cm^{-3}. The cups were then exposed to the simulated rainfall for different durations depending on the rainfall intensity to be tested. The rainfall duration ranged from 18 minutes for 10 mm h^{-1} rainfall intensity to 6 minutes for 30 mm h^{-1}. The rainfall depth was kept constant at 3 mm to avoid any surface pond formation that would have reduced the rainfall energy striking the soil surface. The splash was measured by the difference in the total oven dry weight of each splash cup before and after exposure to simulated rainfall.

3. Results and discussion

3.1 Evaluation of simulated rainfall micro-structure

The rainfall DSD represents the major micro-structural property. Figure 4 shows the DSD measured by the piezoelectric transducer under different rainfall intensities. This result shows that the rainfall simulator generate various drop size under different rainfall intensities, which represent an advantage of the dripper-type rainfall simulators. The large drops number percentage (drops with diameter >2.5) under different rainfall intensities was calculated from results in Figure 4. The simulated rainfall large drops content (%) showed increase pattern with the rainfall intensities. On the other hand, the small drops percentage showed decreasing trend with increasing the rainfall intensities. Figure 5 shows the KE percentage at different raindrop classes (8 classes).

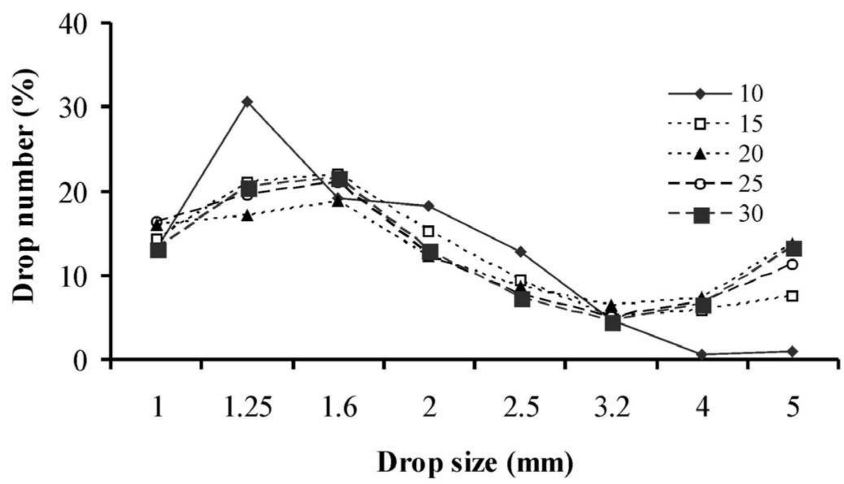

Fig. 4. Simulated rainfall drop size distribution under various rainfall intensities.

The KE pattern was highly different from drops number percentage as the KE resulted from large drops was very high compared to small drops classes. This can be attributed to two reasons: first, the drop mass increases exponentially with diameter; second the raindrop fall velocity has a non-linear relationship with drop diameter. The small drops number and KE percentage is shown in Figure 6. The small drops number and KE percentage showed relative agreement between each other. Both the drops number and KE percentage showed a decrease with rainfall intensities. The large drops number and KE percentage showed increasing pattern with the rainfall intensities. The large drops number percentage is approximately less than 30%, however, the KE produced by this percentage of raindrops was between 70 to 90%. These results emphasize that the large drops number percentage is a determination factor for rainfall KE. The correlation coefficient between the large drops number (%) and KE (%) was 0.78 and this correlation coefficient can be improved by increasing the number of sampled intensities (Figure 7).

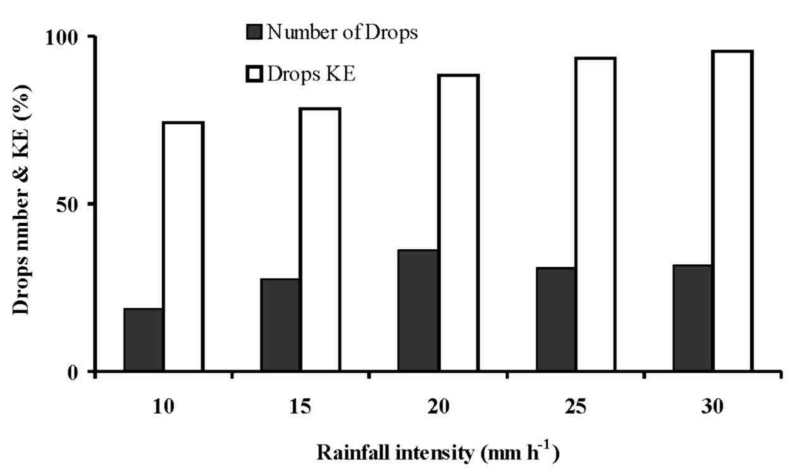

Fig. 5. Relationship between large drops number percentage and kinetic energy percentage under various simulated rainfall intensities.

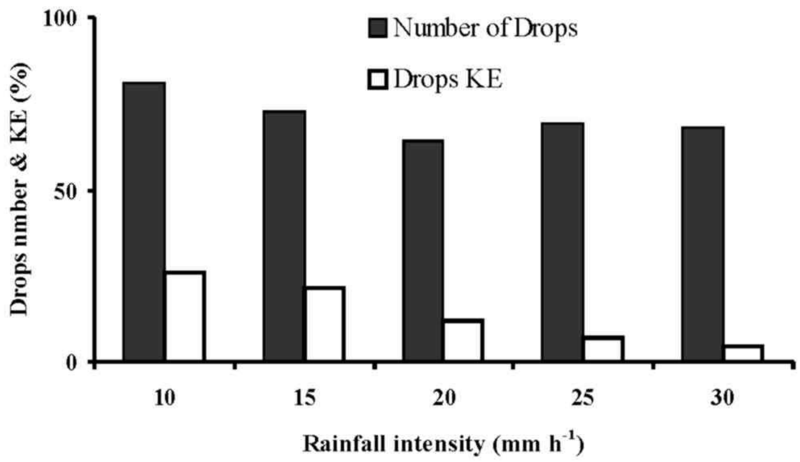

Fig. 6. Relationship between small drops number percentage and kinetic energy percentage under various simulated rainfall intensities.

3.2 Simulated rainfall erosivity

The rainfall erosivity has been represented in this study by the rainfall kinetic energy which was measured using a piezoelectric sensor. Figure 8 shows the relationship between the rainfall intensity and the kinetic energy (I-KE). The simulated rainfall I-KE was also compared with the natural rainfall relationships measured at different geographical locations (Figure 8). The simulated rainfall I-KE relationship showed agreement with the natural rainfall relationships under the observed rainfall intensity range (10 to 30 mm h^{-1}). Generally, I-KE relationship showed increasing and stabilizing pattern with different thresholds. However, different patterns have been also reported by various researchers under different environments (e.g. Hudson, 1963; Carter et al., 1974). The simulated rainfall I-KE relationship, in this study, showed significant agreement with natural rainfall trends.

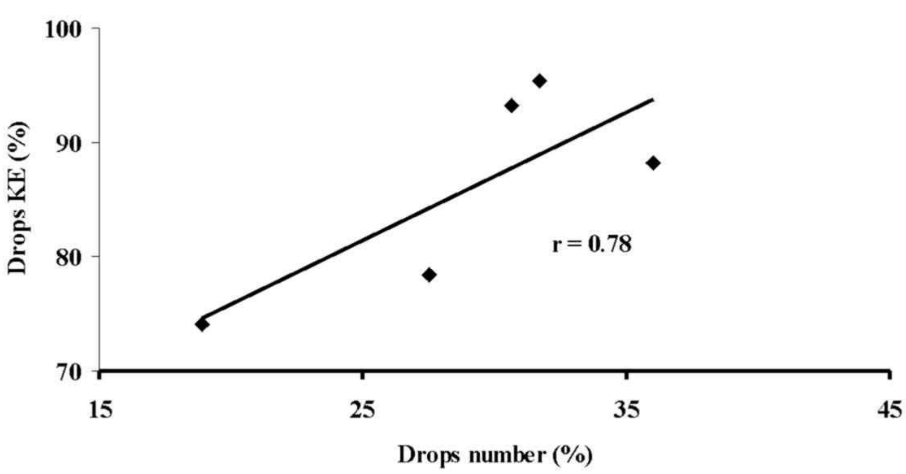

Fig. 7. Relationship between large drops number percentage and kinetic energy percentage under simulated rainfall.

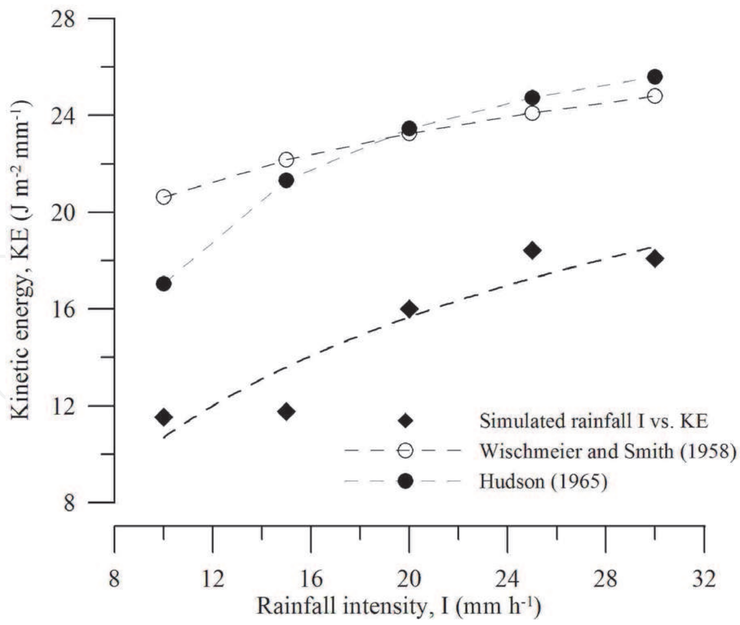

Fig. 8. Simulated rainfall intensity and kinetic energy relationship compared with natural rainfall.

3.3 Rainfall micro-structure and soil erosion

The soil splash erosion can be related directly to raindrop erosivity without any due consideration to the I-KE (Abd Elbasit et al., 2010). In other words, the rainfall erosivity can works as independent splash erosion predictor. As it was shown in the previous discussion, the rainfall micro-structure has significant effects on the rainfall erosivity and consequently on soil erosion. Figure 9 shows the relationship between splash soil erosion and large drops KE percentage.

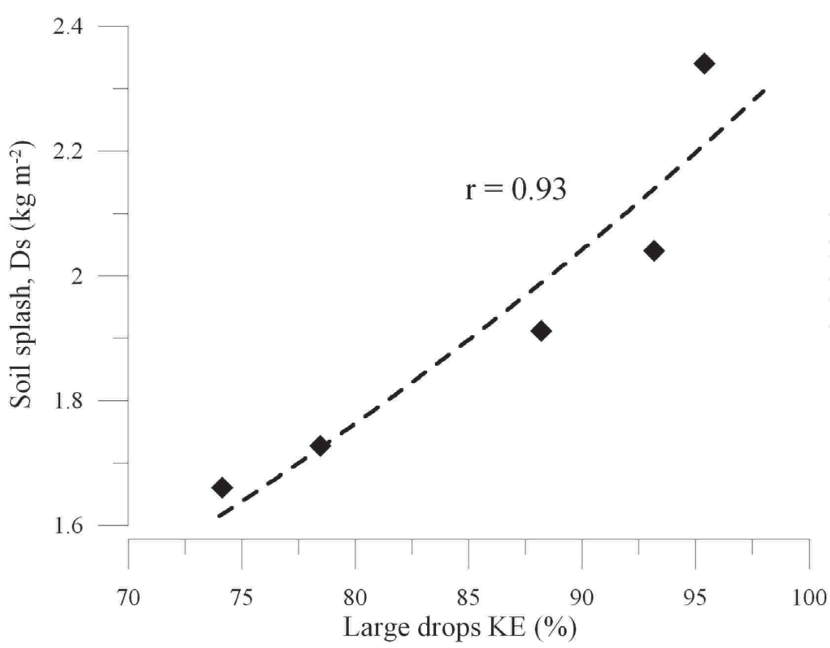

Fig. 9. Splash soil erosion as a function of large drops kinetic energy percentage under simulated rainfall.

4. Conclusions

Rainfall produced by dripper-type rainfall simulator has been charcterized using piezoelectric transducers. The rainfall drop size distribution and kinetic energy has been measured in 10 second time interval. The rainfall micro-structure has been eveluated by the changes in the drop size distribution at each rainfall intensity. The soil splash erosion has been evaluated using splash cup method under five rainfall intensities ranges between 10 to 30 mm h^{-1}. The rainfall kinetic energy was found to increase with the increase in large drops content (drops with diameter > 2.5). The splash soil loss was correlated with the large drop percentage which emphasize that the splash erosion is highly affected by the rainfall micro-structure.

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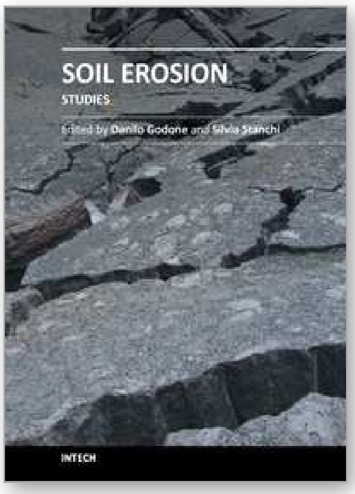

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Soil erosion affects a large part of the Earth surface, and accelerated soil erosion is recognized as one of the main soil threats, compromising soil productive and protective functions. The land management in areas affected by soil erosion is a relevant issue for landscape and ecosystems preservation. In this book we collected a series of papers on erosion, not focusing on agronomic implications, but on a variety of other relevant aspects of the erosion phenomena. The book is divided into three sections: i) various implications of land management in arid and semiarid ecosystems, ii) erosion modeling and experimental studies; iii) other applications (e.g. geoscience, engineering). The book covers a wide range of erosion-related themes from a variety of points of view (assessment, modeling, mitigation, best practices etc.).

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