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Characterizing rainfall erosivity by kinetic power - Median volume diameter relationship

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ABSTRACT

Kinetic power, i.e. kinetic energy per unit time and area, is the variable widely used to represent the rainfall erosivity which affects soil loss and sediment yield. This paper shows the results of an experimental investigation using the raindrop size distributions (DSDs) measured by an optical disdrometer installed at the Department of Agricultural, Food and Forestry Sciences of University of Palermo in Italy (June 2006–March 2014) and at the El Teularet experimental station in Spain (July 2015–May 2016). At first an analysis of the DSDs aggregated into intensity classes is carried out, then the measured kinetic power values are determined. The aggregated DSDs allowed to establish that the median volume diameter of the distribution is affected by raindrops characterized by the greatest values of the diameters that composes precipitation. The measured kinetic power values allowed to verify the reliability of kinetic power-rainfall intensity relationships proposed by Wischmeier and Smith and Kinnell. Finally, using all the available measurements of kinetic power, rainfall intensity and median volume diameter obtained in different climatic contexts and by different measurement techniques, this paper demonstrates that the ratio between kinetic power and rainfall intensity depends strictly only on median volume diameter of the distribution according to a single site-independent relationship. Therefore the estimate of the kinetic energy per unit volume of rainfall does not require the knowledge of the whole drop size distribution. The reliability of a theoretical relationship relating the kinetic power per unit volume of rainfall to median volume diameter is also positively verified using all available measurements.

1. Introduction

The kinetic energy of a given rainfall event represents the total energy which is available to detach soil particles through rain splash (Fornis et al., 2005). The understanding of rainfall characteristics such as Drop Size Distribution (DSD), intensity and kinetic energy is important for the prediction of soil erosion (Meshesha et al., 2014). Despite their importance, not all of these rainfall characteristics are among commonly measured meteorological variables, so researchers have empirically related more easily available measurements, such as rainfall intensity, to rain kinetic energy (Angulo-Martínez et al., 2016).

Rainfall kinetic power, P_n is the kinetic energy per unit time and area ($J\,m^{-2}\,s^{-1}$) and is a hydrological variable used to characterize the erosive power of a rainfall (Nunes et al., 2016), i.e. the rainfall ability to detach and transport soil particles (Cerdà, 1997; Lim et al., 2015).

Many researchers propose empirical relationships linking kinetic power to rainfall intensity having different mathematical forms (Hudson, 1965; Kinnell, 1973; Wischmeier and Smith, 1978; Brown and Foster, 1987; Sempere-Torres et al., 1992; Coutinho and Tomás, 1995; McGregor et al., 1995; Renard et al., 1997; Uijlenhoet and Stricker, 1999; Jayawardena and Rezaur, 2000; Salles et al., 2002).

The most commonly used relationship for estimating P_n ($J\,m^{-2}\,s^{-1}$) is that proposed by Wischmeier and Smith (1978):

$$\frac{P_n}{I} = (11.9 + 8.73 \log I) \tag{1}$$

in which I (mm/h) is the rainfall intensity. Eq. (1) can be applied for rainfall intensity values $I \le I_t$, being I_t the *intensity threshold value* which Wischmeier and Smith (1978) set equal to 76 mm/h. Wischmeier and Smith (1978) also state that for $I > I_t$ the ratio P_n/I ($J\,m^{-2}\,mm^{-1}$) assumes the constant value, calculated by Eq. (1), equal to $28.3\,J\,m^{-2}\,mm^{-1}$.

In other words the ratio P_n/I, which represents the kinetic energy per unit volume of rainfall, increases for rainfall intensity value less than or equal to I_t (Eq. (1)) and it becomes constant (Eq. (1)) for rainfall intensity greater than I_t.

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Wischmeier and Smith (1978) justify this threshold value suggesting that the median volume diameter, D_0, which is the diameter that divides the DSD in two parts of equal volume, stops to continue to increase when rainfall intensities exceed 76 mm/h.

For describing the same trend Kinnell (1981) proposes the following relationship:

$$\frac{P_n}{I} = a\ (1 - b\ \exp(-c\ I)) \tag{2}$$

where a, b and c are parameters. According to Eq. (2) P_n/I has a finite positive value at zero intensity and approaches to the asymptotic value a at high intensity values. Kinnell (1981) states that a parameter can be assumed equal to 29 J m^{-2} mm^{-1} while b and c parameters are site-specific (Salles et al., 2002).

As suggested by Brown and Foster (1987), Eq. (2) is used in the RUSLE model with $a = 29$ J m^{-2} mm^{-1}, $b = 0.72$ and $c = 0.05$ h mm^{-1}. This choice allows to obtain an asymptotic value of P_n/I, which is near to the value obtained by Eq. (1) for $I > 76$ mm/h ($P_n/I = 28.3$ J m^{-2} mm^{-1}). For estimating the rainfall kinetic power Foster (2004) in the RUSLE2 model, suggests the use of Eq. (2) with parameter values proposed by McGregor et al. (1995), i.e. $a = 29$ J m^{-2} mm^{-1}, $b = 0.72$ and $c = 0.082$ h mm^{-1}. Other researchers (Coutinho and Tomás, 1995; Cerro et al., 1998; Jayawardena and Rezaur, 2000) suggest values of a parameter > 29 J m^{-2} mm^{-1} and dependent on geographical location.

Assouline and Mualem (1989) use the Weibull function, as DSD calibrated for five different locations, and the raindrop terminal velocity equation proposed by Mualem and Assouline (1986), for deducing the relationship between the kinetic energy per unit mass and rainfall intensity. The different curves corresponding to the five sites show notable differences and the kinetic energy per unit mass might be represented by a monotonically increasing function or might reach a maximum value and then it could decline for higher rainfall intensity.

Salles et al. (2002), carrying out an overview of many empirical relationships P_n-I, show that, for a fixed rainfall intensity, these relationships yield to very different values of kinetic power. Salles et al. (2002) in agreement with Parsons and Gadian (2000), conclude that a global parameter, as rainfall intensity I or median volume diameter D_0, is not sufficient to characterize rainfall erosivity since kinetic power measurements are also dependent on other effect such as rain type, altitude, climate and method of measurement.

Carollo and Ferro (2015), using about 24000 DSDs detected at Palermo (South Italy) by an optical disdrometer, show that: i) Eq. (1) is fully applicable to rainfall recorded in Sicily; ii) Eq. (2) underestimates the measured P_n values for low rainfall intensity; iii) a power relationship, calibrated by the collected data, overestimates the rainfall kinetic power for high values of I.

In this paper at first the analysis of DSD detected by an optical disdrometer installed in two similar climatic environments, i.e. at Palermo (Italy) and at El Teularet (Spain), and aggregated into rainfall intensity classes, is presented. The aggregated DSDs are used to quantify the median volume diameter of the distribution and the kinetic energy per unit volume of rainfall. The capability of the most widely applied empirical relationships to estimate kinetic power by rainfall intensity is verified. Finally the reliability of a theoretically deduced relationship between kinetic energy per unit volume of rainfall and median volume diameter is also tested.

2. Materials and methods

2.1. Measurement techniques and experimental sites

The DSDs were detected using the same optical disdrometer (model ODM 70 made by Eigenbrodt), installed in two experimental sites located at Palermo (South Italy) and El Teularet (Spain) (Fig. 1).

For each raining minute, the disdrometer measures drop diameter in the range 0.05–0.6 cm. Each drop is separately measured and registered into classes of about 0.005 cm width. The disdrometer divides diameter range into 128 classes and gives the number of drops belonging to a particular class for each recording minute. Drop diameter is measured registering light damping due to the passage of the drop in the control volume between two diodes. This volume has cylindrical shape with a length of 12 cm and a diameter of 2.2 cm. Disdrometer measures simultaneously diameter and falling velocity of the drops that pass through the control volume (Grossklaus et al., 1998; Carollo and Ferro, 2015). The Palermo experimental station is located at the Department of Agricultural, Food and Forestry Sciences of the University of Palermo, at 40 m a.s.l. (Fig. 1a). The climate is Mediterranean temperate (*Köppen's Csa type*), characterized by dry and hot summer and mild and rainy winter. The average annual temperatures range between 15 °C and 22 °C, while rainfalls, mainly concentrated in autumn and winter, show mean annual value of 654 mm.

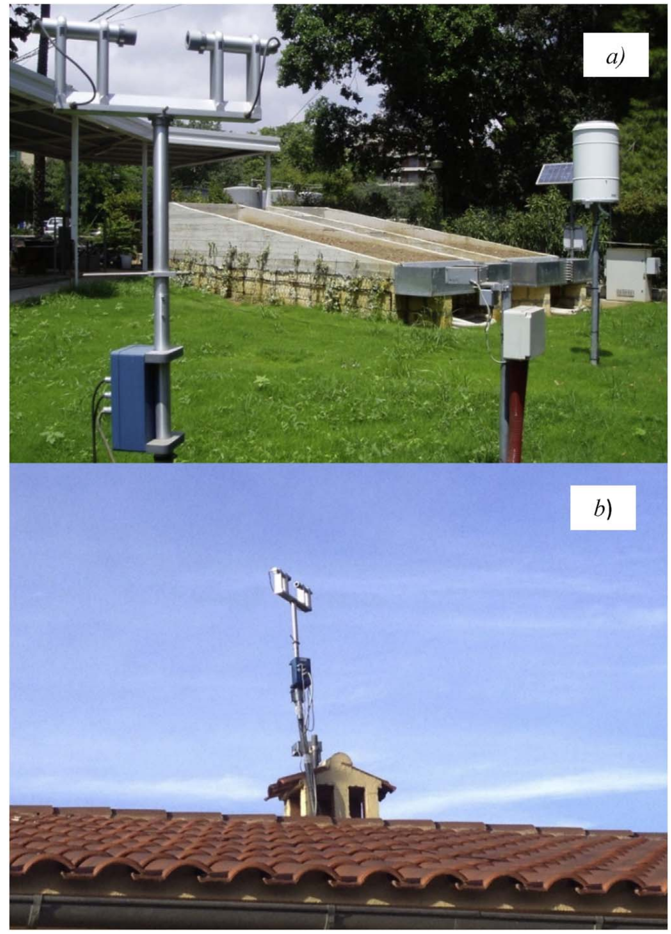

Fig. 1. View of Palermo (a) and El Teularet (b) experimental areas.

The El Teularet experimental site is located at Sierra de Enguera at 100 km southwest from Valencia, at 760 m a.s.l. (Fig. 1b). Climate is typical Mediterranean with 3–5 months of summer drought, usually from late June to September. Mean annual rainfall at the study area range from 479 mm at the Enguera—Las Arenas meteorological station to 590 mm at the Enguera Confederación Hidrográfica del Jucar (CHJ) meteorological station. Rainfall is distributed homogenously among spring, autumn and winter, while the summer is extremely dry due to high temperatures and lack of rainfall (García-Orenes et al., 2009). Mean annual temperature ranges from 12.7 °C at the Enguera—Las Arenas meteorological station to 14.2 °C at the Enguera Confederación Hidrográfica del Jucar (CHJ) meteorological station (García-Orenes et al., 2009).