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# Uncertainties in rainfall kinetic energy-intensity relations for soil erosion modelling

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ABSTRACT

For bare soil conditions, the most important process driving and initiating splash and interrill erosion is the detachment of soil particles via raindrop impact. The kinetic energy of a rainfall event is controlled by the drop size and fall velocity distribution, which is often directly or indirectly implemented in erosion models. Therefore, numerous theoretical functions have been developed for the estimation of rainfall kinetic energy from available rainfall intensity measurements. The aim of this study is to assess differences inherent in a wide number of kinetic energy-rainfall intensity (KE-I) relations and their role in soil erosion modelling. Therefore, 32 *KE-I* relations are compared against measured rainfall energies based on optical distrometer measurements carried out at five stations of two substantially different rainfall regimes. These allow for continuous high-resolution (1-min) direct measurements of rainfall kinetic energies from a detailed spectrum of measured drop sizes and corresponding fall velocities. To quantify the effect of different *KE-I* relations on sediment delivery, we apply the erosion model WATEM/SEDEM in an experimental setup to four catchments of NE-Germany. The distrometer data shows substantial differences between measured and theoretical models of drop size and fall velocity distributions. For low intensities the number of small drops is overestimated by the Marshall and Palmer (1948; MP) drop size distribution, while for high intensities the proportion of large drops is overestimated by the MP distribution. The distrometer measurements show a considerable proportion of large drops falling at slower velocities than predicted by the Gunn and Kinzer (1949) terminal velocity model. For almost all rainfall events at all stations, the *KE-I* relations predicted higher cumulative kinetic energy sums compared to the direct measurements of the optical distrometers. The different *KE-I* relations show individual characteristics over the course of rainfall intensity levels. Our results indicate a high sensitivity (up to a range from 10 to 27 $t\,ha^{-1}$) of the simulated sediment delivery related to different *KE-I* relations. Hence, the uncertainty associated with *KE-I* relations for soil erosion modelling is of critical importance.

## 1. Introduction

Rainfall driven soil erosion is traditionally subdivided into a number of sub-processes, ranging from raindrop impact driven splash and interrill erosion to surface runoff based rill and gully erosion processes. Particularly initial soil erosion processes are closely related to the rainfall kinetic energy (*KE*) that controls soil detachment, aggregate disruption and transport by rain splash. Moreover, rain drop impact on bare soil causes soil crusting and a corresponding infiltration reduction (Morgan, 2005), and leads to turbulences in shallow surface runoff that affects the transport capacity (Kinnell, 2005). Due to these direct and indirect implications of the *KE* of raindrops on several erosion processes *KE* is widely used as an important input parameter in erosion models. It is implemented in conceptual and empirical models, especially the USLE (Wischmeier and Smith, 1960) and its derivatives (RUSLE: Renard et al., 1996; WaTEM/SEDEM: Van Oost et al., 2000) as well as in physically-oriented models (LISEM: De Roo et al., 1996; EUROSEM: Morgan et al., 1998).

The assessment of rainfall *KE* started more than a century ago with the pioneer work of Wiesner (1895) and Bentley (1904) who introduced

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**Table 1**
Table of theoretical relationships for rainfall kinetic energy ($J\,m^{-2}\,h^{-1}$) and rainfall intensity (*I*: $mm\,h^{-1}$; see Fig. 1). Majority of equations are harmonized according to Salles et al. (2002).

| Original reference | Equation | Region |
|---|---|---|
| Logarithmic | | |
| Wischmeier and Smith, 1958 | $I\,(11.9 + 8.73\,\log_{10}I)$ if $I \le 76\,mm\,h^{-1}$; if $I > 76\,mm\,h^{-1}$; KE = $28.3\,J\,m^{-2}\,mm^{-1}$ | – |
| Zanchi & Torri 1980 | $I\,(9.81 + 11.25\,\log_{10}I)$ | Italy |
| Kinnell 1981[a] | $I\,(17.12 + 5.23\,\log_{10}I)$ | USA (Florida) |
| Onaga et al. 1988 | $I\,(9.81 + 10.6\,\log_{10}I)$ | Japan (Okinawa) |
| Brandt 1990 | $I\,(8.95 + 8.44\,\log_{10}I)$ | – |
| Exponential | | |
| McGregor & Mutchler 1976 | $I\,(27.3 + 21.68\,e^{-0.048\,I} - 41.26\,e^{-0.072\,I})$ | USA |
| Kinnell 1981[b] | $29.31\,I\,(1–0.281\,e^{-0.018\,I})$ | USA (Florida) |
| Rosewell 1986[a] | $29\,I\,(1–0.596\,e^{-0.0404\,I})$ | Australia (NSW) |
| Rosewell 1986[b] | $26.35\,I\,(1–0.669\,e^{-0.0349\,I})$ | Australia (Queensland) |
| Brown & Foster 1987 | $29\,I\,(1–0.72\,e^{-0.05\,I})$ | USA |
| Coutinho & Tomás 1995 | $35.9\,I\,(1–0.559\,e^{-0.034\,I})$ | Portugal |
| Cerro et al., 1998 | $38.4\,I\,(1–0.538\,e^{-0.029\,I})$ | Spain |
| Jayawardena & Rezaur 2000 | $36.8\,I\,(1–0.691\,e^{-0.038\,I})$ | China (Hong Kong) |
| Fornis et al. 2005 | $30.8\,I\,(1–0.550\,e^{-0.031\,I})$ | Philippines |
| Intensity power | | |
| Park et al. 1980 | $21.1\,I^{1.156}$ | USA |
| Smith & De Veaux 1992[a] | $13\,I^{1.21}$ | USA (Oregon) |
| Smith & De Veaux 1992[b] | $11\,I^{1.23}$ | USA (Alaska) |
| Smith & De Veaux 1992[c] | $18\,I^{1.24}$ | USA (Arizona) |
| Smith & De Veaux 1992[d] | $11\,I^{1.17}$ | USA (New Jersey) |
| Smith & De Veaux 1992[e] | $10\,I^{1.18}$ | USA (North Carolina) |
| Smith & De Veaux 1992[f] | $11\,I^{1.14}$ | USA (Florida) |
| Uijlenhoet & Stricker 1999[a] | $7.20\,I^{1.32}$ | – |
| Uijlenhoet & Stricker 1999[b] | $8.53\,I^{1.29}$ | – |
| Uijlenhoet & Stricker 1999[c] | $8.46\,I^{1.17}$ | – |
| Uijlenhoet & Stricker 1999[d] | $8.89\,I^{1.28}$ | – |
| Uijlenhoet & Stricker 1999[e] | $10.8\,I^{1.06}$ | – |
| Uijlenhoet & Stricker 1999[f] | $7.74\,I^{1.35}$ | – |
| Steiner & Smith 2000 | $11\,I^{1.25}$ | USA (Mississippi) |
| Shin et al. 2016 | $10.3\,I^{1.22}$ | – |
| Others | | |
| Carter et al. 1974 | $11.32\,I + 0.5546\,I^2–0.5009\,10^{-2}\,I^3 + 0.126\,10^{-4}\,I^4$ | USA (south central) |
| Usón and Ramos, 2001 | $23.4\,I – 18$ | Spain |
| Nyssen et al. 2005 | $36.65\,(I – 0.6/I)$ | Ethiopia |

the filter-paper and fleur pellet method to measure drop size distributions. Later, Laws and Parsons (1943) and Marshall and Palmer (1948) found an exponential relation between drop size distribution (*DSD*) and rainfall intensity and furthermore Laws (1941) and Gunn and Kinzer (1949) developed a model for the terminal velocity of different drop sizes used to calculate drop size specific fall velocities. Linking the models of *DSD* and terminal velocity provided the necessary information to calculate *KE* as a function of rainfall intensity. The most prominent *KE-I* relation in erosion research was published by Wischmeier and Smith (1958). The authors used a relation between *DSD* and intensity from Laws and Parsons (1943) with a combined approach of Laws (1941) and Gunn and Kinzer (1949) of drop size specific fall velocities to calculate rainfall *KE*. Based on the calculated *KE*, a regression equation between *KE* and intensity was derived and used as the basis for the first erosivity index of the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1960). Later, other combinations of *DSD* and drop size specific fall velocities were used to calculate rainfall kinetic energy, whereas the *DSD* of Marshall and Palmer (1948) is the most frequently used (Renard et al., 1997). Based on new rainfall measuring techniques that enable the continuous and simultaneous recording of drop sizes and fall velocities (e.g. optical distrometer), it was shown that drop size and fall velocity distributions can have complex patterns between different storm events (Sempere-Torres et al., 2000), and also vary during different phases within a rainfall event (Angulo-Martinez et al., 2016). To date, a few *KE-I* relations are based on continuous measurements of drop size distributions (e.g. Cerro et al., 1998; Petan et al., 2010; Sanchez-Moreno et al., 2012), but almost no *KE-I* relation is based on both continuously measured drops size and fall velocity distributions. Instead, continuous *DSD* measurements are linked to terminal velocity models (except for Lim et al., 2015). Nonetheless, recent research shows that a large amount of drops is not well represented by terminal velocity models, which might have large implications for deriving rainfall *KE* from intensity (Angulo-Martinez et al., 2016; Larsen et al., 2014; Montero-Martinez and Garcia-Garcia, 2016).

The aims of this study are (i) to analyze potential differences between measured and theoretically derived *KE* using state of the art measuring techniques to directly calculate/measure *KE* from measured drop sizes and fall velocities, (ii) to test a large number of published *KE-I* relations to understand systematic differences between measured and derived *KE-I* relations against the background of regional rainfall regimes and (iii) to use the different *KE* results as input in a water erosion and sediment transport model to quantify the ‘erosion-uncertainty’ associated with different *KE* approaches.

## 2. Materials and methods

### *2.1. Rainfall, drop size distribution and fall velocity data*

#### *2.1.1. Measured and derived rainfall KE*

Rainfall intensity, drop size distribution and drop size specific fall velocity are available at five stations in two different regions of Germany equipped with optical laser distrometers (Laser Precipitation Monitor: Thies-Clima, Germany). The distrometers are mounted at a height of 1 m and record the full spectrum of drop size and fall velocity