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Sensitivity analysis of kinetic energy-intensity relationships and maximum rainfall intensities on rainfall erosivity using a long-term precipitation dataset

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SUMMARY

This paper analyses and compares rainfall erosivity values that were computed with five different kinetic energy-intensity (*KE-I*) relationships using the 0.5-h and 1-h maximum rainfall intensities (I_{30} and I_{60}, respectively). The *KE-I* relationships included three exponential equations (Brown and Foster, 1987 (BF); McGregor et al., 1995 (MG); van Dijk et al., 2002 (VD)), a logarithmic equation (Wischmeier and Smith, 1958 (WS)) and a linear equation (Hudson, 1961 (HU)). The *KE-I* relationships were used to compute rainfall erosivity from pluviographic records of 30 sites that are located in central Chile. A total of 415 years of data were used, and more than 18,000 storms were identified. The results showed that among the exponential equations, the MG relationship yielded erosivity results that were statistically identical to the VD and the BF relationships. However, when comparing the VD and the BF relationships, significant differences in erosivity were found, which showed that the exponential equation is highly sensitive to changes in its regression parameters and is therefore site-specific. Among all of the relationships, the WS logarithmic equation yielded the largest erosivity estimates; however, they were statistically equal to the estimates made with the MG and the VD relationships but were not statistically equal to estimates predicted by the BF relationship. In contrast, in comparison to the other equations, the HU linear relationship yielded significantly smaller erosivity values. Conversely, regardless of the *KE-I* relationship and the site, computing erosivity using I_{60} provided erosivity estimates that are 10% smaller than those obtained using I_{30}. The relative size of the erosivity estimates is due to the relative values of I_{60} and I_{30}; on average I_{60} was 10% smaller than I_{30} at the study sites. Finally, because the rainfall erosivity estimates at the study sites were highly affected by the type of *KE-I* relationship, these results demonstrate that selecting an appropriate *KE-I* relationship is crucial for accurately estimating erosivity. These differences were augmented because of the typically low rainfall intensities at the study sites. Under this condition, the differences between the *KE-I* relationships were greatest. However, with higher rainfall intensities, all of the *KE-I* relationships provide similar kinetic energy estimates, which makes the selection of the *KE-I* relationship less important than the use of a reliable I_{30} value for computing rainfall erosivity.

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1. Introduction

Rainfall kinetic energy is a commonly used climatic parameter for the prediction of soil erosion by water (Roswell, 1986; Lobo et al., 2015). This parameter has often been used as an indicator of rainfall erosivity, which is the capability of rainfall to detach soil particles (van Dijk et al., 2002). Widely used indices of erosivity, such the relationships proposed by Hudson (1961), Govers (1991) and the *R*-factor of the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997), include rainfall kinetic energy. In these relationships the kinetic energy is not linearly related to the soil loss. This is mainly caused by the typical small size of raindrops in low-intensity rainfall events; small raindrops are less efficient at detaching soil than larger raindrops (Salles and Poesen, 2000). On the other hand, high rainfall intensities are more likely to produce saturation and ponding, which may increase the efficiency of detachment (Torri et al., 1987). In the case of the RUSLE equation, the erosivity of each individual storm was defined as the kinetic energy of the storm multiplied by the

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maximum 0.5-h rainfall intensity (I_{30}), while erosivity was defined as the average of the annual summation of each storm's erosivity (Renard et al., 1997). Thus, estimating rainfall erosivity using this definition requires having a reliable measure of the rainfall kinetic energy and sub-hourly rainfall measurements.

Several methods have been developed to measure and estimate rainfall kinetic energy (Abd Elbasit et al., 2011). Estimating kinetic energy from rainfall intensity records by using empirical kinetic energy-rainfall intensity (*KE-I*) relationships is the most widely used method. Many types of mathematical formulations that are derived from measured precipitation intensity and calculated kinetic energy data have been proposed to describe *KE-I* relationships (Salles et al., 2002). Wischmeier and Smith (1958) proposed the following logarithmic relationship:

$$KE = a + b\log(I) \tag{1}$$

where *KE* is the kinetic energy of rain that is falling with intensity *I*, and *a* and *b* are constants that are derived from a nonlinear regression using actual data. This relationship was calibrated with data from 60 sites in 31 eastern states in the USA (Wischmeier, 1959) and was used in the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978). On the other hand, Hudson (1961) proposed the following linear relationship:

$$KE = a^{-1}(b - cI^{-1}) \tag{2}$$

where *a*, *b* and *c* are regression parameters. This equation was calibrated for subtropical climates in Zimbabwe and was adopted in the Soil Loss Estimator Model for Southern Africa (SLEMSA) (Elwell, 1978). This linear equation also proved to be valid for rainfall data that were collected in Miami (Kinnell, 1973). Later, Kinnell (1981) developed this exponential equation:

$$KE = e_{max}(1 - ae^{-bI}) \tag{3}$$

where e_{max} is the maximum kinetic energy content of the rainfall, and *a* and *b* are regression parameters. This relationship provides kinetic energy values that are similar to those of the logarithmic equation, however it should be preferred because, unlike the logarithmic equation, it is a continuous equation with a physical meaning. The exponential equation was calibrated by Brown and Foster (1987) and incorporated in the RUSLE model. However, the equation used in RUSLE2 was that developed by McGregor et al. (1995), which is based on Eq. (3) but was calibrated for more sites that were located in Mississippi (Foster, 2008).

Even though all of these equations are, to some degree, based on drop size distribution and drop velocity (Fox, 2004), there is no consensus regarding which equation best represents rainfall kinetic energy (Shamshad et al., 2008). In addition, their regression parameters have proven to be different and highly dependent on geographic location (Fornis et al., 2005), which limits their use on sites that are different from those that were used to build and calibrate them. Therefore, when using these equations to compute rainfall erosivity in sites where no kinetic energy records are available, it is important to consider that erosivity estimates will vary depending on the selected *KE-I* equation. Similarly, if there are no readily available sub-hourly rainfall records to compute the I_{30} values, which is a typical condition in many countries all over the world (Yin et al., 2007), the erosivity estimates may vary according to the I_{30} estimation method. These methods include using Intensity–Duration–Frequency (IDF) curves (Wenzel, 1982) and Bell's equation (Bell, 1969), which provide different I_{30} estimates. Erosivity estimates are highly sensitive to I_{30} (Catari et al., 2011); thus choosing the appropriate estimation method is crucial to compute a reliable erosivity value. Therefore, the objective of this study was to perform a sensitivity analysis of the various *KE-I* relationships and I_{30} estimation methods on rainfall erosivity using a long-term precipitation dataset from central Chile.

2. Materials and methods

2.1. Study sites and rainfall data

Hourly pluviographic records were used to compute rainfall erosivity values at 30 sites that are located in central Chile. These records were obtained from the meteorological stations that are shown in Fig. 1, which are distributed between latitudes 32°04′S and 39°47′S. The stations are part of two national rain gauge networks that are managed by the Dirección General de Aguas (DGA) and the Sistema Nacional de Calidad del Aire (SINCA). As shown in Table 1, the amount of data per station ranged from 3 to 28 years and totaled 418 years and 18,012 storms. Depending on the station, the rainfall data were recorded between 1970 and 2013. Annual data were missing at some stations. The climate in this portion of Chile is mainly semi-arid, and the rainfall is usually of a frontal nature (Escobar and Aceituno, 1998), with intensities that rarely exceed 5.5 mm/h (Table 1). Additionally, precipitation amounts increase with latitude, and rainfall is highly erosive in some areas because of prolonged storms, especially in the southern sites of the study area (Bonilla and Vidal, 2011; Lobo et al., 2015).

2.2. KE-I relationships

Five *KE-I* relationships were used to compute rainfall erosivity at the study sites (Table 2). These relationships consisted of three types of equations, one logarithmic, one linear, and three exponential and were developed by Wischmeier and Smith (1958), Hudson (1961), Brown and Foster (1987), McGregor et al. (1995) and van Dijk et al. (2002), respectively. The equations are shown in Table 2 and are plotted against rainfall intensity in Fig. 2. As shown in the figure, the differences among the equations decrease with increasing rainfall intensity. The differences among the equations are especially large at low rainfall intensities (<5 mm h^{-1}), which is the typical condition in central Chile (Table 1). This is particularly important in the case of Hudson's equation, which was developed for subtropical climates with high rainfall intensities (Nel and Sumner, 2007) and not for a semi-arid climate with low rainfall intensities. Nevertheless, this equation was included in this comparison to assess its applicability under a different climate condition.

2.3. Estimation of I_{30}

Estimating erosivity requires computing I_{30} for each storm. Unfortunately, as in many other places in the world, this parameter is not usually recorded in Chile. Therefore, I_{30} values were estimated using the Intensity–Duration–Frequency (IDF) curve that was developed by Wenzel (1982), which is based on the 1-h rainfall records as follows:

$$I = \frac{K}{D^n + b} \tag{4}$$

where *I* is the storm's mean intensity (mm h^{-1}) for duration *D* (h), and *K*, *n* and *b* are regression parameters. To fit the parameters, the intensities for durations of 1–6 h were computed for each storm, and a non-linear regression was used. Then, I_{30} was computed for each storm using Eq. (4) with the fitted parameters. Table 1 shows the average I_{30} that were estimated with this method, which are 8–14% larger than the 1-h maximum intensities, I_{60}, depending on the station. The similarities between the I_{30} and I_{60}

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