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Kinetic energy estimation by rainfall intensity and its usefulness in predicting hydrosedimentological variables in a small rural catchment in southern Brazil

Rafael Ramon [a,*], Jean P.G. Minella [a], Gustavo H. Merten [b], Claudia A.P. de Barros [a], Tiago Canale [a]

[a] Department of Soils, Federal University of Santa Maria, Av. Roraima 1000, Building 42 – Office 3311A, Postal 97105-900, Santa Maria, RS, Brazil
[b] Large Lakes Observatory, University of Minnesota Duluth, Research Laboratory Building 109, 55812-3024, Duluth, MN, United States

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ABSTRACT

One of the challenges of modern agriculture is to adapting to climatic effects, including the capacity of rainy events in causing erosion. The understanding of these phenomena relies on monitoring rain variables that express the magnitude and pattern of erosive agents. Kinetic energy (E) is a fundamental variable to represent the erosivity and to enable the estimation of erosion and sediment yield in mathematical models. In Brazil, there are no direct and continuous measurements of E, and empirical equations to estimate rainfall intensity (I) are used instead. As a result, empirical equations to estimate E from I are used. To assess local behavior between these variables, rain variables (energy, volume and intensity) and associated processes (water flow (Q) and suspended sediment concentration (SSC)) were measured in a small rural catchment. The work was developed in a small rural catchment (1.23 km^2) located in southern Brazil where intensive land use with tobacco cultivation has caused high rates of erosion and sediment yield. This study proposes an alternative equation E = f(I) for the study region and provides a comparison with previous equations already proposed by Foster et al. (1981); van Dijk et al. (2002); Wilkinson (1975); Brown and Foster (1987) and USDA-ARS (2013). Furthermore, this work explores the seasonal variations and the differences in the magnitude of the events of these relationships. The measured E values were similar to those estimated by the equations of Foster et al. (1981); USDA-ARS (2013) and van Dijk et al. (2002), whereas Brown and Foster (1987) underestimate the estimation of E. Finally, it was evaluated the predictive ability of the total kinetic energy, 30 min maximum intensity (I_{30}) and total volume of the rainfall (P_{total}) in explaining the response variables which reflect the hydrology and sediment yield processes considering the Q and SSC. The main results of the work were: i) a new equation to estimate E based on the I measured, its seasonal variation and similarity with the previously known equations and ii) the relationship between E and the hydrological variables at catchment scale.

1. Introduction

The rise in the intensity and amount of precipitation has been the cause of investigation of the erosive processes, which along with soil use and management changes represent a critical point in the triggering and increase of soil erosion and runoff generation (Nearing, 2001; Nearing et al., 2005). Climate and land use are dynamic factors that control the magnitude of the erosive process, which can be quantified by response variables in the catchment, for example, the sediment yield (Zhou et al., 2002). To represent the climate factor, it is common to use the erosivity that represents the capability of the rainfall (climate) in causing soil erosion. Quantification of erosivity (EI_{30}) is based on the kinetic energy (*E*) of the raindrop times the maximum rain intensity in 30 min (I_{30}), which expresses the capability of forming concentrated runoff (Wischmeier and Smith, 1978). Knowledge of *E* enables the understanding of the erosive potential of each rainfall event, since this variable has a direct relationship with the detachment processes (Hammad et al., 2006). Thus, it is expected that E contributes in explaining the variability of suspended sediment concentration (SSC) and sediment yield (SY) in catchments (Duvert et al., 2010), especially those characterized by high rates of erosion and connectivity between the sources and drainage network.

The characteristic of rain represents the entrance of matter and energy that propagates in the landscape. Part of this energy is dissipated in the form of detachment (splash and flow) and transport (Morgan, 2005). Therefore, the understanding of the erosive process depends on

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* Corresponding author at: Department of Soils, Federal University of Santa Maria, Av. Roraima 1000, Building 42 – Office 3312, Postal 97105-900, Santa Maria, RS, Brazil.
E-mail addresses: rafaramon11@gmail.com (R. Ramon), jminella@gmail.com (J.P.G. Minella), mertengh@gmail.com (G.H. Merten), dinhaufsm@gmail.com (C.A.P. de Barros), tiagocanale94@gmail.com (T. Canale).

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the precise quantification of the amounts of energy that reach the surface soil, its consequences in the drainage network and the connection between both processes (Zhou et al., 2002). Water and soil loss during a rainfall event is driven not only by the quantity and intensity of the rain, but also by its energy (Duvert et al., 2010). Overland flow, which is a result of the infiltration process, is affected by the formation of surface crust resulting from the energy of the raindrop (Stolte et al., 1997; Zhou et al., 2013). In this way, E together with a runoff volume estimator (maximum intensity of 30 min - I_{30}) is closely linked to the formation of overland flow and erosion processes in the catchment. However, it is important to note that flow behavior is also dependent of other phenomena, such as affluence variable areas (Dunne and Black, 1970; Hewlett and Hibbert, 1967) in which there is overland flow even in low intensities of rain. Thus, soil management strategies as well as mathematical modeling depend on the characterization of the contribution of the climate control factor by means of E and I in the pattern of response variables that characterize the catchment system.

In Brazil, no records of direct and continuous measurements of E have been found until now. The direct measurement of E relies on specific equipment, resulting in higher costs (Fornis et al., 2005). Hence, empirical relations between E and I, which were developed in different regions, most notably in the United States, are used.

The influence of different rain patterns, which are influenced by particularities of the local climate, can cause uncertainty in regards to extrapolation in different regions, especially among temperate, tropical and subtropical regions (Kinnell, 1981; McIsaac, 1990; Van Dijk et al., 2002). According to Morgan, (2005), there are also seasonal differences led by frontal or convective rainfall that determine important differences in the characteristics of the drops.

Given the importance of rainfall erosivity in understanding erosive processes, proposing conservation measures and using erosion prediction models (Bertol et al., 2008; Lombardi Neto and Moldenhauer, 1992), a great number of studies were carried out to estimate the rainfall erosivity in different regions of Brazil (Bazzano et al., 2007, 2010; Bertol et al., 2002; Cassol et al., 2008; Eltz et al., 2011; Oliveira et al., 2012; Rufino et al., 1993; Silva, 2004). However, as in these cases the energy is estimated from I with empirical equations developed in other regions of the world (Foster et al., 1981; Wischmeier and Smith, 1958), the applicability of the equation needs to be evaluated.

In this context, the automatic measurement energy enables the acquirement of temporal variation of rain erosivity loyal to the study site. For this, the disdrometer may be used to measure the drop size distribution and velocity in short intervals, such as in the work of Petan et al. (2010); Jaffrain and Berne (2011), and Raupach and Berne (2015). The precise estimation of E patterns of rain and its influence on the hydrological and erosive processes at catchment scale are essential for the definition of soil and water conservation practices in the adaptation of agriculture to climate change. Further progress in the management of natural resources depends on mathematical modeling techniques of water flow and associated elements, from its origin up until the response in the rivers. Therefore, the comprehension of local singularities as well as the provision of data is crucial for the composition of a global database covering the different regions of the planet.

Considering the importance of the expansion of the worldwide database of E measurement for the estimation of erosivity as a function of I, as well as the need to understand specific local features of the relationship between rain energy and the responses in flows and erosion, this work presents a set of measured E data as well as an analysis of its potential use in the catchment scale. Thus, the objectives of the study were: i) to examine the relationship of $E = f(I)$ using a representative set of precipitation events considering the seasonal variability and different magnitudes of rain events; ii) to compare the local relationship $E = f(I)$ with empirical equations commonly used; and iii) to assess the predictive capacity of E in explaining the water and sediment discharge variability in a small catchment with high rate of sediment yield.

2. Methods and materials

2.1. Characterization of the study area

The experimental catchment of the Lajeado Ferreira creek possesses 1.23 km^2 of drainage area and can be found on the slopes of the Brazilian southern plateau, in the city of Arvorezinha - RS, which is a typical headwater catchment (Fig. 1). The local geology is characterized by volcanic rocks with varying elevations of 580–730 m, the relief on the upper part is rolling (slope $<$ 7%), and the middle and lower third relief are strongly undulating ($>$15%) with short slopes and enclosed valleys. The corresponding classes of soils in the catchment are the Acrisols, which are characterized by an increase of clay in the subsurface layer, and Cambisols and Leptosols, which are shallow and stony. The mapping was carried out in the field in detailed soil classification survey (1: 5000), according to the IUSS Working Group WRB (2006). In the autumn and winter, the local rainfall pattern is characterized by long-term low intensity frontal-type rainfall. The spring and summer seasons (September to March) are dominated by thermal convective rains of high intensity and short duration. In September and October, the rainfall with the most erosive ability occurs, with high intensity and longer duration events. Rural properties have around 10 ha and are characterized by low technological level and diversified land use. The main crops in the catchment during the monitoring period are: *Nicotiana tabacum* (13.1%), grain crops (24%), *Eucalyptus* spp. (34.8%), grassland (5.2%), native forest (15.5%) and others (7.4%).

2.2. Rainfall monitoring

The E was monitored using an optical laser disdrometer, model OTT - Parsivel^2. The instrument consists of two lenses, one emitting and one receiving, which are separated by a 54 cm^2 laser beam (30 × 180 mm). A photodiode converts the laser into a voltage signal. When a particle passes through both lenses, there is a break in the signal and a reduction in the area detected for a certain time. Through the area that is reduced and the duration of the signal interruption, it is possible to detect the diameter and particle velocity, respectively (Löffler-Mang and Joss, 2000).

The other variables (volume and duration) were measured with the disdrometer and also with two pluviometers and two rain gauges (Fig. 1) in order to observe the spatial variability. A local observer measured the cumulative daily rain in pluviometers (model Ville de Paris) and the intensities are recorded by rain gauges and the disdrometer at 10 min intervals. The rainfall database consists of the accumulated rain - P (mm), rain intensity - I (mm h^{-1}) and kinetic energy per unit of time - E_{time} (J m^{-2} h^{-1}).

2.2.1. Rain erosivity

According to Wischmeier and Smith (1978), the concept of rainfall erosivity is the product of E times the I_{30} (Eq. (1)), which is a statistical relationship that reflects how the total energy and peak intensity are combined in each particular rainfall event.

$$EI_{30} = E \times I_{30} \tag{1}$$

In this work, we established a link between I and E measured in 10 min intervals in order to establish a characteristic equation of the specific conditions of southern Brazil and its explanatory power of the main effects of water erosion in the catchment.

In addition, E values measured using the disdrometer were compared with estimated values using E estimating equations commonly used in southern Brazil. Energy equations used to compare with the E measured in this study were: Foster et al. (1981)(Eq. (2)), van Dijk et al. (2002) (Eq. (3)), Wilkinson (1975) (Eq. (4)), Brown and Foster