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Multivariate models for annual rainfall erosivity in Brazil

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ABSTRACT

Water erosion has been considered as the most important worldwide environmental problem, being especially caused by intense rainfall events. The potential of rain to generate soil erosion is known as rainfall erosivity and its estimation is fundamental for the understanding of climatic vulnerability of a given region. This work aims to develop models for estimating mean annual rainfall erosivity for Brazilian regions based on multiple linear regression, using latitude, longitude and altitude as predictors for the models. Equations for rainfall erosivity estimations as function of the Modified Fournier Index (MFI) were acquired from 54 Brazilian pluviographic stations (termed as “Main Stations” in this work) to generate the database for this study. These equations were applied to estimate mean annual rainfall erosivity for 773 different rain gauges taking into account historical series with at least 15 consecutive years of daily precipitation and considering the similarity of the Precipitation Concentration Index (PCI). These rain gauges contain only pluviometric records, thus allowing the rainfall erosivity calculation in function of MFI in accordance with the order of PCI. The goodness-of-fit of each model was evaluated taking into account the adjusted coefficient of determination and the significance level of each variable. Moreover, the mean absolute error, bias of estimation, and the residual probability distribution were evaluated for other 155 rain gauges which were used exclusively for validation. All the adjusted multivariate models presented acceptable values for the statistical coefficients, being possible to estimate the mean annual rainfall erosivity for any location in Brazil using only its geographical coordinates and altitude. An annual rainfall erosivity map was created for Brazil based on the multivariate models and ordinary kriging map for residuals derived from the models (regression-kriging technique). It can be concluded that this map resulted in a spatial distribution of EI_{30} better than the former map and, in addition, it can be considered an important update related to the rainfall erosivity study in Brazil since more representative data sets were used.

1. Introduction

Water erosion has been treated as one of the most important worldwide environmental problem, mainly in tropical and subtropical agricultural lands. One of the most important active agents of soil erosion is rain due to its potential for producing soil disaggregation and consequently splash of soil particles. This potential is also known as rainfall erosivity and it is absolutely important in the context of soil erosion prediction.

Rainfall erosivity maps have been used as input for various environmental analyses related to the spatial distribution of soil erosion. A common approach is the Universal Soil Loss Equation (USLE), which has been applied especially for regions with scarce climatological data sets by employing computational techniques available in GIS (Beskow et al., 2009; Bhattarai and Dutta, 2007; Ozcan et al., 2008; Shamshad et al., 2008).

Conceptually, rainfall erosivity is a variable defined as a function of rainfall kinetic energy and maximum 30-minute rainfall intensity (Wischmeier and Smith, 1978). For a potential rainfall erosivity estimation of a given individual rainfall event, it is essential to analyze the respective pluviographic records. Nevertheless, the use of this kind of data is difficult, and requires a lot of time for processing (Kinnell, 2010; Petan et al., 2010). The main concern is related to the lack of long-term pluviographic records for many developing countries in the world, including Brazil (Beskow et al., 2009; Mello et al., 2007; Shamshad et al., 2008).

To overcome the problem of data scarcity for individual analysis of a rainfall event, various equations have been proposed to estimate mean monthly rainfall erosivity. The most commonly applied method, which is known as Modified Fournier Index (MFI), is based on the mean monthly and annual rainfall (Renard and Freimund, 1994). MFI has been frequently used in many countries with the

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purpose of estimating annual rainfall erosivity and developing rainfall erosivity and soil loss maps (Beskow et al., 2009; Lujan and Gabriels, 2005; Mannaerts and Gabriels, 2000; Nigel and Rughooputh, 2010; Ozcan et al., 2008). Based on this procedure, annual rainfall erosivity maps have been developed for countries or states (Mello et al., 2007; Oduro-Afriyie, 1996; Qi et al., 2000; Salako, 2010; Silva, 2004).

Rainfall erosivity maps can be generated with the aid of geostatistical procedures, which can be used considering altitude as secondary variable, or a local spatial interpolator like Inverse Square Distance (Goovaerts, 1999; Mello et al., 2007; Qi et al., 2000; Salako, 2010; Silva, 2004). Nevertheless, the practical use of these maps includes to locate a given place over the map and to extract its respective value based on the class interval, i.e., the users don't estimate a specific value for a given site; they simply have a spatial distribution of values without taking into account other physiographical properties of landscape such as continental and topographical properties.

Marquínez et al. (2003) adjusted multivariate models to estimate the mean annual precipitation and mean precipitation during dry and wet periods for the Asturias region in Northern Spain as a function of latitude, longitude, altitude, distance from coast and some other topographical variables. These authors found good statistical precision (given by the adjusted coefficient of determination) for the models, ranging from 0.58 to 0.67 (residuals had no pattern or bias) and mean absolute error ranging from 8 to 26 mm (13.3% to 19.5%). Mello and Silva (2009) adjusted similar models to predict mean annual precipitation, mean precipitation for the dry and wet periods in Minas Gerais State, southeastern Brazil, as a function of latitude, longitude and altitude, and obtained results ($R^2 > 0.75$) better than the ones found by Marquínez et al. (2003).

As mean annual and monthly precipitation predictions based on the geographical coordinates are possible (Goodale et al., 1998; Marquínez et al., 2003; Mello and Silva, 2009), there are evidences that the same procedure may be applied to estimate mean monthly rainfall erosivity, as demonstrated by Meusburger et al. (2012) for Switzerland, Diodato and Bellocchi (2010) for Mediterranean region in Italy, Angulo-Martinez et al. (2009) for the Ebro region in Spain, and Goovaerts (1999) for the Algarve region in Portugal. Multivariate models have a different practical use, since they allow users to predict values of climatic variables for a specific place with good accuracy. One of the most important characteristics of a GIS regression model, classified by Angulo-Martinez et al. (2009) as a global interpolator, is that it does not rely on neighbors for interpolation. In addition, it is important to mention that regression-based approaches for estimating rainfall erosivity have demonstrated to be capable of making good estimations when applied for large regions characterized by complex atmospheric systems and sparse samples, such as in Brazil, especially for North-Midwest regions (Daly et al., 2002; Meusburger et al., 2012).

Angulo-Martinez et al. (2009) fitted a multiple regression model to estimate the rainfall erosivity for Ebro region in Spain, considering as predictors elevation, latitude, longitude and solar radiation, extracting all these variables from a DEM. The authors verified, based on the stepwise procedure, that solar radiation was not significant, structuring their model on the basis of latitude, longitude and elevation, however, a small coefficient of determination (smaller than 0.3) was found. In this context, Meusburger et al. (2012) evaluated a multiple linear regression model for estimating rainfall erosivity for Switzerland, making use of both log-transformation of erosivity dataset and stepwise procedure. They found that latitude and longitude were not significant and, consequently, these variables were excluded of the model. On the other hand, annual precipitation and altitude were found to be significant and the final model was based on these variables, resulting in a coefficient of determination of 0.68. Despite the collinearity detected between altitude and annual precipitation, Meusburger et al. (2012) opted to keep the model in its original structure because the model based on only precipitation or altitude caused heteroscedasticity of the residuals, corresponding to a non-normal distribution of them.

The integration of GIS and multivariate modeling procedures enables practitioners to produce more accurate maps of mean climatic characteristics. Thus, they can aid soil conservation practitioners to estimate the potential rainfall erosivity for a specific location and to provide important scientific information. However, the combination of a map generated by multivariate models, which are adjusted employing geographical and topographical characteristics as input variables, and a map of the residuals produced by the models, obtained by kriging, can be more precise for assessing maps. This integrated interpolator is known as regression-kriging and Meusburger et al. (2012) and Angulo-Martinez et al. (2009) applied this concept to generate a rainfall erosivity map for Switzerland and Ebro basin (Spain), respectively, and got better predictions for the maps in comparison with other interpolators.

In the context described above, this study has as objectives to develop multivariate models for estimating mean annual rainfall erosivity to Brazilian geographical regions having Latitude, Longitude and Altitude as independent variables and to develop a new annual rainfall erosivity map for Brazil based on the regression-kriging technique.

2. Material and methods

2.1. Site description, database and calculation of annual rainfall erosivity

Brazil is a continental country with latitude ranging from 5°N to 35°S and longitude from 35°W to approximately 74°W and altitude from 0 to 2600 m. Due to these aspects, there are very different climatic regions, but Brazil is predominantly a tropical and wet country. Nevertheless, there are several exceptions as follows: (i) the countryside of Northeast region presents a warm and dry climate, typical of semi-arid regions; (ii) South and parts of Southeast regions can be characterized by cool temperatures due to southern latitudes (extra-tropical regions) and, or, mountainous influence; (iii) precipitation distribution for the Southeast region is characterized by a large amount of rain concentrated within 6 months, especially during the summer; (iv) for the South region, we can find a better temporal precipitation distribution throughout the year. These aspects are important to characterize the rainfall intensity pattern differences and consequently, the potential of rainfall erosivity. The amount of precipitation in Northeastern Brazil is considerably less than that in other Brazilian regions; however, it is much more concentrated, therefore the respective rainfall erosivity can be significant.

Daily rainfall records were obtained through HIDROWEB/ANA portal (www.ana.gov.br) for rain gauges distributed over Brazilian regions (Fig. 1). Long-term daily rainfall series (with at least 15 consecutive years) were used, seeking data sets as recent as possible. As a result, 773 long-term daily rainfall series were used for the calibration phase and 155 for the validation. The latter set of pluviometric stations was chosen randomly considering approximately 20% of the total dataset per region, similar to the procedure adopted by Viola et al. (2010) and Vicente-Serrano et al. (2007). The former study was related to modeling and mapping of annual and monthly precipitation for Minas Gerais state (Brazil), while the latter evaluated reference evapotranspiration for Ebro valley region (Spain). Although 928 time series have been chosen for this study, there are over 2500 pluviometric stations whose databases can be downloaded from the website mentioned earlier. However, many of them present old data sets with the last records in 1980s or 1990s and contain a large amount of gaps. It should be emphasized that as criterion only those rain gauges with recent data sets (ending in 2000s) and with series longer than 15 years consecutive were chosen. In addition to this, there is a good spatial distribution of the rain gauges over the