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Development of an appropriate procedure for estimation of RUSLE EI_{30} index and preparation of erosivity maps for Pulau Penang in Peninsular Malaysia

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Abstract

Pluviographic data at 15 min interval from 6 stations in Pulau Penang of Peninsular Malaysia were used to compute rainfall erosivity factor (R) for the revised universal soil loss equation (RUSLE). Three different modelling procedures were applied for the estimation of monthly rainfall erosivity (EI_{30}) values. While storm rainfall (P) and duration (D) data were used in the first approach, the second approach used monthly rainfall for days with rainfall ≥10 mm ($rain_{10}$) and monthly number of days with rainfall ≥10 ($days_{10}$). The third approach however used the Fournier index as the independent variable. Based on the root mean squared error (RMSE) and the percentage error (PE) criteria, models developed using the Fournier index approach was adjudged the best with an average PE value of 0.92 and an average RMSE value of 164.6. Further, this approach was extended to the development of a regional model. Using data from additional sixteen stations and the Fournier index based regional model, EI_{30} values were computed for each month. ArcView GIS was used to generate monthly maps of EI_{30} values and also annual rainfall erosivity (R). The rainfall erosivity factor (R) in the region was estimated to vary from 9000 to 14,000 MJ mm ha^{-1} h^{-1} $year^{-1}$.

Keywords: Rainfall erosivity; Pluviographic data; EI_{30} values; Revised universal soil loss equation; Soil erosion

1. Introduction

Information on the extent of soil erosion is vital to many professionals such as civil and construction engineers for the design and construction of buildings, roads, dams and utility lines, urban and forest managers for the assessment of erosion hazards and even agriculturists and soil scientists engaged in the preservation of soil loss through soil conservation strategies (Obi and Salako, 1995; Sonneveld and Nearing, 2003). Some of the factors that control the extent of sheet and rill erosion of soils are climate, topography, soil type and land use. Erosion rates greatly depend on the erosive forces that are generated due to impact of raindrops and soil resistance to its detachment and transport. In the humid tropics, erosion due to water can be very high specifically in areas with steep slopes and poor soil structure. As a result, rainfall erosivity factor *(R)* is considered as one of the most important factors in soil loss estimation while using universal soil loss equation (USLE) (Wischmeier and Smith, 1978) or in the revised universal soil loss equation (RUSLE) (Renard et al., 1997) which is given by:

$$A = LS \times R \times K \times C \times P \qquad (1)$$

where A is the rate of soil loss in t ha^{-1} $year^{-1}$, R is the rainfall erosivity factor in MJ mm ha^{-1} h^{-1} $year^{-1}$ {is computed as total storm energy (E -MJ/m^2) multiplied by the maximum 30 min intensity (I_{30}-mm/h)}; K is the soil erodibility factor (t h MJ^{-1} mm^{-1}); L is the slope length factor; S is the slope steepness

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factor; C is cover management factor; and P is the conservation support practice factor. It can be seen from the RULSE that, when other factors do not change, the rate of soil loss is directly proportional to the value of rainfall erosivity. Besides this, since data required for each of the factors in the RUSLE can be represented in geographic information system (GIS) format, the GIS procedures can therefore be applied to estimate the aforesaid factors and predict erosion in a grid cell easily.

The advantage of the USLE or RUSLE model is that it has been widely used and tested over many years and the validity and limitations of this model are already known (Renard et al., 1997). The disadvantage of this model is that it was developed using data from the Midwest of the USA, and therefore significant adjustments are required to the algorithms used to derive the key factors before the model can be applied to other areas. In Malaysia, the model was often used for the assessment of soil erosion but with limited evaluation (Roslinah and Norizan, 1997; Kamaruzaman and Baban 1999; Zulkifli, 2000; Gregersen et al., 2003). Large variations exist in the estimation of soil erosion. This is due to the availability of limited data and relevant information for calculating the factors; especially the rainfall erosivity factor. Also, due to the unique climatic conditions in the sub-catchments, the rainfall erosivity factor requires special consideration (Millward and Mersey, 1999). Realistic estimation of monthly rainfall erosivity EI_{30} values requires long term pluviographic data at 15 min intervals or less (Wischmeier and Smith, 1978). In many parts of the world, especially in developing countries, spatial coverage of pluviographic data is often difficult to obtain (Yu et al., 2001; Cohen et al., 2005). Monthly, seasonal and annual rainfall data are usually available for longer periods and are generally used to calculate R; hence are likely to end up in an inaccurate estimation of erosivity values or for that matter render the RUSLE less useful. Use of annual precipitation ignores the bimodal variability of rainfall (Bhuyan et al., 2002) within the year and even the regional seasonality which in some cases are necessary for two or more parallel analyses for specific seasons. In spite of such shortcomings, rainfall erosivity estimation using rainfall data with long time intervals have been attempted by several researchers. For example, Morgan (1986) suggested the following empirical equation for Peninsular Malaysia for predicting annual erosivity (EVa) using the mean annual rainfall (P):

$$\mathrm{EVa} = 9.28P - 8838 \quad (2)$$

It predicts the annual values of Hudson's KE >25 index but does not include an EI_{30} term. Therefore, the predicted values cannot be used directly in RUSLE or USLE as they do not represent the R values needed for that approach. To bring in the effects of seasonality, Mati et al. (2000) developed two different regression models for R factor with annual rainfall data after separating the data into two groups based on the location of stations in a particular agro-climatic zone. More recently, using the pluviographic data of Colombian Andes (1987–1997), Natalia (2005) developed yet two more regression models, one for the wet and the other for the dry season. To generalize the findings, these models were used to estimate seasonal erosivity for 10 other stations in the country, though their usefulness is yet to be ascertained. In some cases, knowledge of the quantity of storm rainfall and its duration has been used to estimate EI_{30} values (Mannaerts and Gabriels, 2000). Multiple linear regression models relating monthly EI_{30} values with monthly rainfall for days where rainfall exceeds 10 mm ($rain_{10}$) instead of mean monthly rainfall, and monthly number of days where rainfall exceeds 10 mm ($days_{10}$) instead of simple rain duration, were developed for the Algarve region of Portugal (Goovaerts, 1999; Loureiro and Coutinho, 2001). Even, models taking quadratic forms and using annual rainfall have been suggested by Morgan (1995) and Millward and Mersey (1999). Besides these, many researchers have found good relationships between the rainfall erosivity and the Fournier index (Arnoldus, 1980; Morgan, 1986; Coutinho and Tomas, 1994; Oduro-Afriyie, 1996; Silva da, 2004). For example Arnoldus (1980) used this technique for the estimation of rainfall erosivity in some regions of USA and even in some regions of Africa, while Coutinho and Tomas (1994) used this for the estimation of rainfall erosivity for three different locations in the south of Portugal.

The rainfall erosivity map can be produced after the computation of erosivity values for each station using any of the methods mentioned above and then undertaking interpolation for finding *iso*-pluvial values using geographic information (GIS) applications. To produce soil erodibility nomograph for Malaysia, Hui (1999) used Morgan's (1986) approach. As such an annual erosivity map for Peninsular Malaysia was developed using the annual rainfall data in Eq. (2) and the mean annual erosivity (Eva) values for this region seemed to vary from 10,000 in the west coast to 25,000 J m^{-2} in the east coast. Similar attempts, using different equations given by different researchers, have been made by Qi et al. (2000) and Silva da (2004) to generate the rainfall erosivity map for the Republic of Korea and Brazil respectively. Most of these equations however were based on Fournier index.

In spite of the several approaches used so far for accurate estimation of rainfall erosivity, no comprehensive study comparing the various aspects of different modelling procedures has been reported so far. Particularly there is no validated equation that can be used appropriately to compute the monthly rainfall erosivity for matching its typical climatic conditions. In the present study, attempts to estimate monthly rainfall erosivity (EI_{30}) values for Pulau Penang in Peninsular Malaysia using three different modelling procedures have been made so that the choice of an appropriate model could be made using the error criteria. As such, Rainfall erosivity maps of Pulau Penang in Malaysia were created to study the spatial and temporal characteristics of rainfall erosivity in the study area.

2. Study area and data

The present study has been undertaken for the state of Pulau Penang in the west coast of Peninsular Malaysia which is about 370 km from Kuala Lumpur, the capital city. The state consists of a part of the mainland and also an island in the west with Georgetown as its capital. The state is divided into 5 municipalities namely, Central Seberang Perai, North Seberang Perai, South Seberang Perai, the Northeast and the Southwest.