Development of rainfall erosivity isohyet map for Peninsular Malaysia

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Abstract
This article describes the development of a rainfall erosivity map for Peninsular Malaysia. Prior to the release of a national level isohyets map for rainfall erosivity (R) factor, soil loss estimation using Universal Soil Loss Equation (USLE) or its revised version (RUSLE) requires manual computation of R factor from the users. This practice induces uncertainties and discrepancies in soil loss estimations due to the use of different computation procedures and spatial approximation methods. This manuscript documents a standardized computation of R values using 10-year rainfall records from 241 rain gauges in the peninsula. The processes of data preparation, analysis and mapping are described herein. The developed isohyets map provides valuable R factor data for easy application of USLE-based soil loss models in Malaysia.

Key words: Rainfall erosivity; universal soil loss equation; spatial approximation; isohyets map; GIS.

1. Introduction
The Universal Soil Loss Equation (USLE) or its revised version, RUSLE, is the single most commonly used model for soil loss estimation. Both models are quite similar to each other, with the revised version improved in parameter derivations. These two conceptual models can be expressed through an equation as shown in Equation 1. The rainfall erosivity factor, R is used in the USLE (Wischmeier and Smith, 1978) or RUSLE model (Renard et al., 1997) to represent the erosion potential of rainfall. When factors other than rainfall are held constant, soil losses from cultivated fields are directly proportional to a rainstorm parameter, which is the total storm energy (E) times the maximum 30-minute intensity (I). R factor is the annual averaged sum of EI values for all qualified storms in a year. It can be more clearly expressed in Equation 2 below.

\[ A = R.K \cdot LS \cdot C \cdot P \]  

\[ R = \frac{A}{K \cdot LS \cdot C \cdot P} \]  

Where
- A - Annual soil loss, in tonnes ha⁻¹ year⁻¹
- R - Rainfall erosivity factor, an erosion index for the given storm in MJmmha⁻¹h⁻¹
- K - Soil erodibility factor, the erosion rate for a specific soil in continuous fallow condition on a 9% slope of 22.1m length, (tonne/ha)/(MJmmha⁻¹h⁻¹)
- LS - Topographic factor which represent the slope length and slope steepness. It is the ratio of soil loss from a specific site to that from a unit site having the same soil and slope but with a length of 22.1m.
- C - Cover factor, which represents the protective coverage of canopy and organic material in direct contact with the ground. It is measured as the ratio of soil loss from land cropped under specific conditions to the corresponding loss from tilled land under clean-tilled continuous fallow (bare soil) conditions.
- P - Management practice factor which represents the soil conservation operations or other measures that control the erosion, such as contour farming, terraces, and strip cropping. It is expressed as the ratio of soil loss with a specific support practice to the
corresponding loss with up and down slope culture.

\[ R = \frac{1}{n} \sum_{j=1}^{n} \left( \sum_{k=1}^{m} (E_j)(I_{30}/k) \right) \]  

(2)

Where \( E \) is the total storm kinetic energy, \((MJ/ha)\), \( I_{30} \) is the maximum 30 minutes rainfall intensity, \((mm/hr)\), \( j \) is the index for the number of years used to compute the average, \( k \) is the index of the number of storms in each year, \( n \) is the number of years to obtain average \( R \), and \( m \) is the number of storms in each year.

\( EI \) is an abbreviation for energy times intensity and the term should not be considered simply an energy parameter. Data show that rainfall energy alone is not a good indicator of erosive potential. A long and less intense rain event might have the same rainfall energy of a short but intense rain event, but the degree of erosive potential might not be as great because the potential of raindrop erosivity is also associated with intensity. The \( I_{30} \) component reflects the prolonged peak rates of detachment and runoff. The product term \( EI_{30} \) is a statistical interaction term that reflects how total energy and peak intensity are combined in each particular rainfall event. Technically, the term indicates how particle detachment is combined with transport capacity (Renard et al., 1997).

The USLE/RUSLE has been widely applied for has been widely applied throughout the world for soil loss estimation and catchment land management. It has been successfully applied in many countries including China (Shi et al., 2004 and Ma et al., 2003), Australia (Erskine et al., 2002), India (Singh et al., 1992), Uganda (Lufafa et al., 2002) and Malaysia (Hashim et al., 1995), to name a few. The model is simple and easy to use, making it a popular tool among researcher and catchment managers. In more advanced studies, researchers modified the equation or method of computing the factors to suit local conditions. Examples of such cases are reported by Morgan (1974), Cohen et al. (2005) and Bagarello et al. (2011).

Among the many factors, computation of R factors appeared to be the most complicated due to the rainfall data requirement. Extensive research has been conducted to provide end user with ‘ready-made’ R factors computed based on rainfall of a region or country. This information is often presented as isoerodent maps. Isoerodent maps for US (Renard et al., 1997), Nigeria (Salako, 2010), Spain (Angulo-Martinez et al., 2009), Brazil (da Silva, 2004), Jordan (Eltaif et al., 2010), and Korea (Lee and Hoo, 2011) are just a few examples of such work.

There have been isolated studies in Malaysia to develop rainfall erosivity map, although most concentrate on a small study area, e.g. Penang Island (Shamshad et al., 2008; Pradhan et al., 2011) and Cameron Highlands (Midmore et al., 1996). Soil loss study has been carried out rather frequently in Malaysia, mostly as part of the Environmental Impact Assessment (EIA) and Erosion and Sediment Control Plan (ESCP) requirements enforced by the Malaysian Government on specific developments. Despite it being a legitimate requirement, there are no guidelines on how soil estimation assessment was to be carried out. DOE (1996) emphasize the need for ESCP but failed to describe the design for the required facilities, which would have to be based on accurate soil loss assessment. For that reason, it is not uncommon to have conflicting assessments of a same study area due to different soil loss assessment approach. For example, while both Pradhan et al (2011) (652.81 MJ.mm/ha.h) and Shamshad et al (2008) (11,500 MJ.mm/ha.h) studied rainfall erosivity factor in Penang Island, the difference in the reported average value was so huge that it is difficult to decide which is valid.

Therefore, a unified standard should exist to allow soil loss to be assessed in a more objective manner, not only within a single study, but also across several studies. It would tremendously help decision makers to refer other research and make comparison before any development is being approved. In order to achieve this, DID published the Guideline for Soil Erosion and Sediment Control for Malaysia (DID, 2010) with a complete set of isoerodent maps representing the rainfall erosivity of Peninsular Malaysia. This paper discusses the technical details of the guideline that would finally produce the set of complete isoerodent maps for Peninsular Malaysia.

### 2. Data collection and cleaning

#### 2.1 Data Type and Source

The required precipitation data was provided Department of Irrigation and Drainage (DID) Malaysia. 10-minute rainfall records from 241 rain gauge stations scattered around the peninsula (Figure 1) were retrieved. Table 1 categorises the number of stations according to state. Then the data are screened, cleaned and finally formatted in a pre-analysis process to produce a complete and continuous rainfall records database suitable for producing isoerodent map. The methodology of the entire process is represented in a flow chart as given in Figure 2. Detailed procedure of each step was being described in following text.

The collected data is required to derive the rainfall erosivity and finally produce the isoerodent maps. Hence, this data provide continuous 10-minute interval rainfall records to calculate maximum 30-minute rainfall intensity. For most stations, the data collected ranges from 1999 to 2008 to derive the average annual R factor and isoerodent maps based on the latest rainfall temporal and spatial patterns respectively.
2.2 Estimating Missing Precipitation Records

In this study, rainfall records of one single station over one complete calendar year was referred to as a dataset. As R factor is computed by averaging annual sum of EI30, the collected rainfall data required screening to ensure no missing values or dates are present within a year. Should gaps (missing records) are found, the gaps would require to be ‘filled in’ by a record patching procedure, which involves statistical interpretation and recreation of rainfall records based on hydrological similarity of the stations. These hypothetical/ synthetic replacements are not suitable to represent large portion of data, or otherwise the resulting EI30 will lose its authenticity. Therefore, dataset with missing data of more than 3 months were excluded from R factor calculation.

For incomplete datasets (rainfall records for one year that contain missing values) gaps of less than 3 months were ‘patched up’ using statistical method, i.e. normal-ratio method (Equation 3). The method is conceptually simple and uses average annual rainfall to derive weights for rainfall depth at individual stations at a particular time. The method can be mathematically written as,

$$\bar{P}_x = \sum_{i=1}^{n} w_i P_i$$

(3)

Where, \( \bar{P}_x \) is the estimated rainfall depth at station \( x \); \( w_i \) is the weight for station \( i \) calculated based on annual rainfall depth, \( A_x \); \( A_i \) is the average annual rainfall at station \( i \); and \( P_i \) is the corresponding rainfall depth at station \( i \). In order to simplify and achieve better accuracy of estimating missing values, additional hydrological criteria was added in to ascertain that nearby stations portray hydrological similarity to the subject station. All nearby stations were screened based on these criteria:

- The nearby station shall not be more than 50km further than the subject.
- Annual difference between nearby station and subject should be less than 10%.
- Monthly rainfall distribution should have at least 0.75 correlations between both stations.

The 2410 datasets were filtered using the criteria determined to segregate suitable and unsuitable datasets for R factor analysis. Incomplete data were required to be filled in, and further screened using criteria stated above. After the entire screening process, only 1749 (72.5%) data sets out of 2410 data sets qualified for determination of R factor. Table 2 summarise the status of data sets from 241 rain gauge stations.

<table>
<thead>
<tr>
<th>No.</th>
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<th>No. of Station</th>
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3.0 Computation of Rainfall Erosivity (R) Factor

In this study, the rainfall erosivity index, $R$, is calculated from Equation 2 shown in earlier text. The total storm kinetic energy for each storm, $E$, is obtained by summation of the product of unit kinetic energy and the respective rainfall volume of all the increments in a rainfall event, as given in Equation 4 below:

$$E = \sum_{r=1}^{K} e_r V_r$$  \hspace{1cm} (4)

Where, $E$ is the total storm kinetic energy; $K$ is the number of storm intervals; $R$ is the index number of storm intervals; $e_r$ is the unit kinetic energy for the $r^{th}$ interval; and $V_r$ is the total rainfall depth for $r^{th}$ interval.

The energy of a rainfall event is a function of the amount of rain and of all the storm’s component intensities. The median raindrop size generally increases with greater rain intensity (Wischmeier and Smith, 1978) and the terminal velocities of free-falling water drops increase with larger drop size. Since the energy of a given mass in motion is proportional to velocity squared, rainfall energy is directly related to rain intensity. Zainal (1992) presented the equations that describe the relationship as below:

$$e_r = 210 + 89 \log_{10}(i_r) \quad i_m \leq 7.6 \text{ cm/hr}$$  \hspace{1cm} (5)

$$e_r = 288.4 \quad i_m > 7.6 \text{ cm/hr}$$  \hspace{1cm} (6)

Where $i_r$ is the average rainfall intensity of the $r^{th}$ interval. The unit for unit energy given by Equation 5
and 6 is tonne-meter per hectare per centimetre of rainfall (ton.m/ha.cm).

The calculation towards determining R factor is given as below:

i. Computing $EI_{30}$ for every individual rainfall event,
ii. Accumulating $EI_{30}$ of each year in study duration,
iii. Average up the annual $EI_{30}$ sum to obtain R factor.

In order to calculate $EI_{30}$ for each storm event, individual storms need to be identified beforehand in each dataset. A dry period between two independent storm events was used as the separation criteria for this purpose. This dry period is defined as a period with recorded rainfall sum of less than 12.7mm over 30 continuous minutes. Figure 3 shows an example of how an individual storm is identified and its $EI_{30}$ calculated. The entire process from identifying individual storm to computing $EI_{30}$ is carried out using Microsoft Excel Spreadsheet with Macro Script.

Annual $EI_{30}$ calculated for each data set was computed using the same spreadsheet (an example is showed in Figure 4). It can be observed that the some extreme values are obtained most probably due to technical error during data collection (at site/ during data storing). These extreme values, which were considered as outliers, are excluded from the averaging process to avoid disrupting the statistical geometry of datasets. The same set of tables also present the final average annual rainfall erosivity, R factor. The value was obtained by averaging the calculated annual accumulated $EI_{30}$ of the complete data sets within each station. Extreme values mentioned earlier on were excluded from the averaging process.

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<tr>
<th>(A)</th>
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<td>Time</td>
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<td>Total P</td>
<td>Duration</td>
<td>Intensity</td>
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4.0 Spatial interpolation for result mapping

Geographical Information System (GIS) software was used to spatially interpolate the results of R factor and to convert point form result (rain gauge) into raster form. The method used to achieve this is kriging. Kriging is based on statistical models that include autocorrelation—that is, the statistical relationships among the measured points. Because of this, not only do geostatistical techniques have the capability of producing a prediction surface, they also provide some measure of the certainty or accuracy of the predictions (ESRI, 2009).

Kriging assumes that the distance or direction between sample points reflects a spatial correlation that can be used to explain variation in the surface. Kriging fits a mathematical function to a specified number of points, or all points within a specified radius, to determine the output value for each location. Kriging is a multistep process; it includes exploratory statistical analysis of the data, variogram modelling, creating the surface, and (optionally) exploring a variance surface (ESRI, 2009). In derivation of R factor isorodent map, kriging is one of the more common methods used (Shamshad et al, 2008, Angulo-Martinez et al, 2009) because developer can cross validate the generated erodent map with original points and made proper calibration as required.

The kriging parameters used in this study is shown in Table 3 below. The result yield from this setting gives a reasonably good spatial regionalisation of the R factor for Peninsular Malaysia. After kriging is completed, the produced raster is further cleaned and smoothened using smooth line tools. This is to ensure a regionalised distribution of R factor, which will be easier for user to extract required R factor during practical applications.

Figure 3 An Example of spread sheet application for individual event $EI_{30}$ computation
Contribute immensely for soil loss estimation and subsequent planning. While it lacks in quantitative accuracy, it provides sufficient indication and relative comparison figures for planning and design purposes.

The derived R factor isohyets map is based on procedure described by Renard et al. (1997). Admittedly, there are several uncertainties still revolve around the procedure and resulting R factor map. Further research is currently being carried out to investigate several aspects of developing the R factor. Among the scopes of research include:

- The unit energy empirical equation (Equation 5 and 6) - current equations are adopted directly from RUSLE model, while Malaysian rainfall might induce different unit energy.
- Classification of individual rainfall and cut-off value for rainfall depth - both are currently set based on research experience. Further research is being planned for physical verification of such methods.
Method of spatial interpolation - currently only krigging method is explored. Other methods will be explored to provide the best method for spatial interpolation of R factor isohyet map. While the current version of R factor isohyets map may have some drawbacks, it nevertheless represents a significant step ahead in erosion control and planning for the country. At the very least, it is the first unified source of R factor for Peninsular Malaysia. The map allows an objective comparison of soil loss or erosion rates at a reasonable accuracy level.

Figure 5 Rainfall erosivity map for Peninsular Malaysia
6.0 Conclusion

This article documents the process of developing a rainfall erosivity (R factor) isohyets map for soil loss prediction using USLE or RUSLE in Peninsular Malaysia. 10-minute precipitation records over a period of 10 years for 241 hydrological stations throughout the peninsula are collected. The article describes a procedure of preparing data for R factor computation, including estimation of missing data. The method used to define individual storm, as well as El30 computation were also presented. Finally, the results are mapped using Krigging method to produce an isohyets map of R factor for Peninsular Malaysia. Admittedly, the developed map still has several short comings, including the accuracy of derived value, and method of spatial interpolation. The authors are looking forward for future research in addressing these uncertainties. Nonetheless, the product of this research has provided the nation with a single and standardised R factor source to be used to improve erosion and sediment control in the country.

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References

5. DID or Department of Irrigation and Drainage (2010). Guideline for Erosion and Sediment Control in Malaysia, Department of Irrigation and Drainage, Malaysia
6. DOE or Department of Environment (1996). Guidelines for Prevention and Control of Soil Erosion and Siltation in Malaysia, Department of Environment, Malaysia.
9. ESRI, or Environmental Science Research Institute (2009). Kriging, ArcGIS Desktop Helpfiles, ESRI.


