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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_{30}). *R* factor is the annual averaged sum of EI_{30} values for all qualified storms in a year. It can be more clearly expressed in Equation 2 below.

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

Where
A - Annual soil loss, in *tonnes* ha^{-1} $year^{-1}$,
R - Rainfall erosivity factor, an erosion index for the given storm in $MJmmha^{-1}h^{-1}$,
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) / (*$MJmmha^{-1}h^{-1}$*)*,
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.

$$R = \frac{1}{n}\sum_{j=1}^{n}\left[\sum_{k=1}^{m}(E)(I_{30})_k\right] \quad (2)$$

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 Heo, 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.

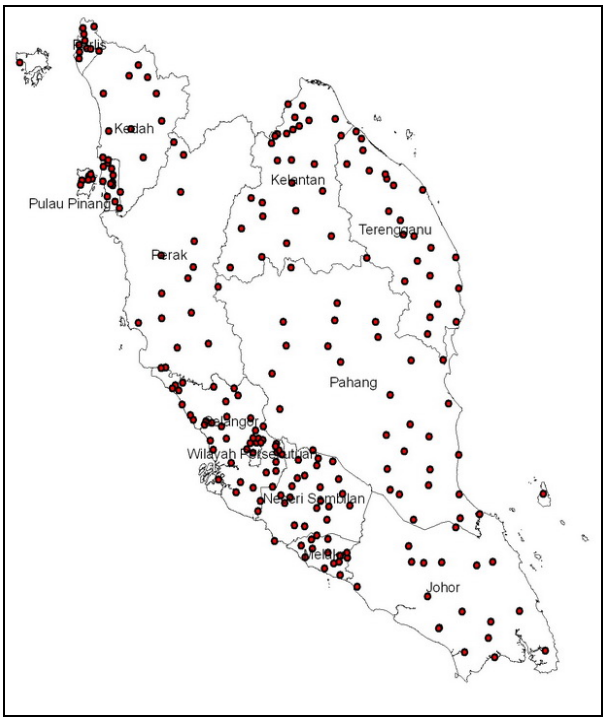

Figure 1 Spatial distribution of collected rain gauge stations for Peninsular Malaysia

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 EI_{30}, 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 EI_{30} 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,

$$\hat{P}_x = \sum_{i=1}^{n} w_i P_i \tag{3}$$

Where, $\hat{P}_x$ is the estimated rainfall depth at station x; w_i is the weight for station i calculated based on annual rainfall depth, $= \frac{A_x}{n \times A_i}$; A_x is the average annual rainfall at station x; n is the number of station used in the method; 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 1 Number of stations with 10 minutes records in Peninsular Malaysia

No.	States	No. of Station
1.	Johor	22
2.	Kedah	10
3.	Kelantan	27
4.	Melaka	14
5.	Negeri Sembilan	21
6.	Pahang	31
7.	Pulau Pinang	20
8.	Perak	14
9.	Perlis	11
10.	Selangor	37
11	Terengganu	24
12.	Wilayah Persekutuan	10
	Total	241

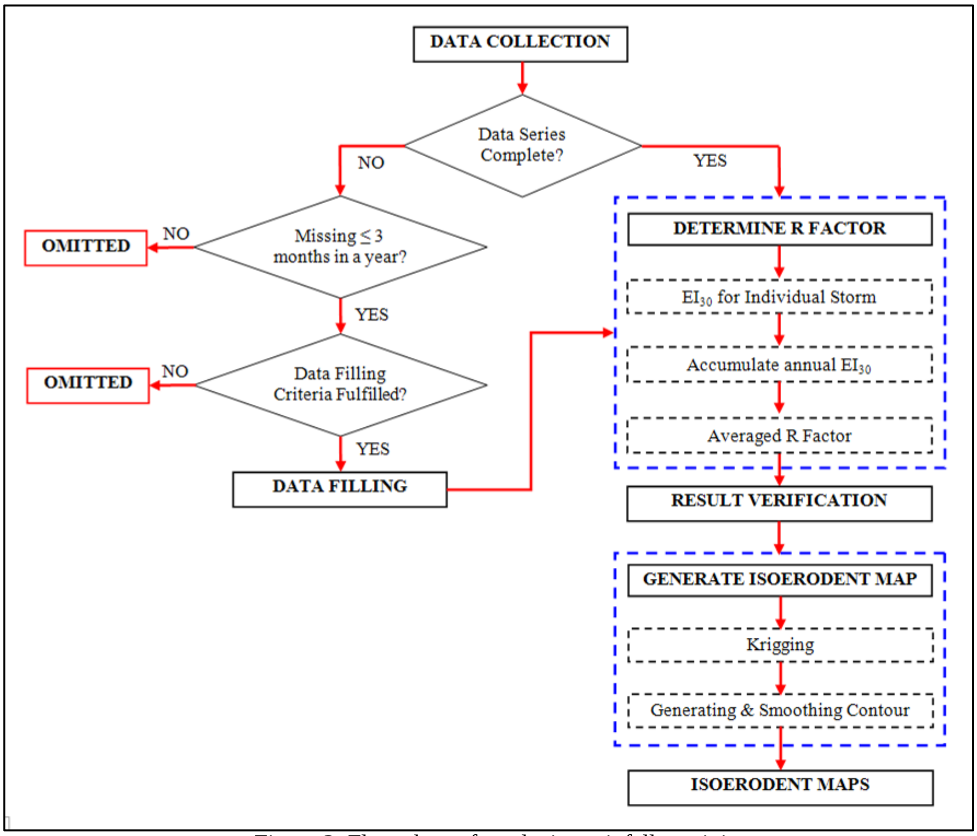

Figure 2: Flow chart of producing rainfall erosivity map

Table 2 Statistical Summary of data set for R factor calculation

Condition code		Data set Status	Count	% of Total
1	(green)	Complete (post processing not required)	820	34.0
2	(yellow)	Data Incomplete but filled (<3 month missing, filling criteria fulfilled)	929	38.6
3	(orange)	Data Incomplete & not filled (< 3 months missing, filling criteria unfulfilled)	225	9.3
4	(purple)	Dataset excluded (> 3 months missing)	335	13.9
5	(grey)	No Data (Totally no data)	101	4.2
		TOTAL	2410	100

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:

$$E = \sum_{r=1}^{k} e_r V_r \qquad (4)$$

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:

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

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

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.

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 isoerodent map, kriging is one of the more common methods used (Shamshad el 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.

(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)	(J)	(K)	(L)
Rain	Date	Time	Event	Total P	Duration	Intensity	I_{30}	e	E	EI_{30}	EI_{30}
1/10 mm				cm	Hr	cm/hr	cm/hr	Ton.m/ha.cm	Ton.m/ha	Ton.m^2/ha.hr	MJ.mm/ha.hr
0	20040225	152000									
0	20040225	153000									
0	20040225	154000									
0	20040225	155000									
45	20040225	160000	START	5.60	1.33	4.2	6.70	265.469	1486.627	99.604	977
100	20040225	161000									
55	20040225	162000									
165	20040225	163000									
110	20040225	164000									
60	20040225	165000									
20	20040225	170000									
5	20040225	171000	BREAK								
0	20040225	172000									
0	20040225	173000									
0	20040225	174000									
5	20040225	175000									
0	20040225	180000									
0	20040225	181000									

Figure 3 An Example of spread sheet application for individual event EI_{30} computation

Station No.	Station Name	District	Long	Lat	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	R Factor
2630001	Sg. Pukim	Rompin	103.057	2.603		12,474	8,896	10,471	18,892		3,993				10,945
2634193	Sg. Anak Endau Kg. Mok	Rompin	103.458	2.617	15,655	33,854	27,834	20,266	35,470	24,201	24,044	20,113		13,160	24,311
2828173	Kg. Gambir	Pekan	102.856	2.850		14,010			8,324						11,167
2829001	Ulu Sg.Chanis	Rompin	102.938	2.813	6,333	21,020	9,657	10,254	16,604		12,596	12,789			12,744
2831179	Kg. Kedaik	Rompin	103.186	2.889	4,303	781,309	285,061	13,999	20,514	20,684	1,190,794				14,875
2834001	Stn. Pertanian Rompin-Endau	Rompin	103.450	2.813	1,682	6,715	39,893	20,083	36,337	37,503	21,076	20,413	24,108		23,090
2841001	"Takek,Pulau Tioman"	Pulau Tioman	104.165	2.818	15,120	15,196	20,673	19,990	35,401	33,474	14,074				21,990
2924096	LDG.GLENDALE	Kuala Pilah	102.419	2.938		24,545					12,268				18,406
3028001	Sg. Kepasing	Pekan	102.832	3.021	8,921	23,645	15,996	7,216	9,114	10,024	11,246	10,699			12,108
3032167	Temeris	Pekan	103.199	3.017			13,987	15,356	23,937	14,478				17,005	16,940
3121143	Simpang Pelangai	Bentong	102.197	3.175	12,312	12,271				2,589	13,587				10,190
3129177	Bkt. Ibam	Pekan	102.976	3.168	10,681	16,879	19,563	16,975	17,404					16,518	16,300
3134165	Dispensari Nenasi di Pekan	Pekan	103.442	3.138	19,362	12,744	28,470	16,790	22,848	14,477				19,117	19,115
3228174	Sg. Cabang Kanan	Rompin	102.822	3.299	79,126	19,407	19,570	13,284	21,962	13,512	18,897	20,518	25,065		19,027
3231163	Kg. Unchang	Pekan	103.189	3.288	15,680	20,743	22,008	15,963	16,288	17,602	14,429	29,925	11,464	20,393	18,449
3330109	Kampong Batu Gong	Pekan	103.026	3.390	18,332	16,114	19,869	12,453	15,463	15,900					16,403
3519125	Kuala Marong di Bentong	Bentong	101.915	3.513	6,595	11,617	6,395	9,052	134,792		13,388	21,067	14,273	16,051	12,305
3533102	Rumah Pam Pahang Tua di Pekan	Pekan	103.357	3.561	26,978	7,026	23,657	13,661	34,423	9,645	23,115	19,824	19,262	19,725	19,732
3628001	Pintu Kawalan Paya Kertam	Temerloh	102.856	3.633	11,129		11,703			1,955	3,869				7,164
3818054	Stor JPS Raub	Raub	101.847	3.806	6,877	14,158		15,700	6,605	8,191	8,136	13,651			10,474
3924072	Rumah Pam Paya Kangsar	Jerantut	102.433	3.904	6,342	16,266	11,814	15,588	7,710	8,223	22,494	8,838	8,800	12,069	11,814
3930012	Sg. Lembing P.C.C.L Mill	Kuantan	103.036	3.917	12,988	20,222	34,197	12,606	22,768	17,706	15,766	20,412	16,120	17,164	18,995
4019001	JKR Benta	Lipis	101.967	4.033		11,924		16,202							14,063
4023001	Kg. Sg. Yap	Jerantut	102.325	4.032			17,547	665			3,422	11,998			8,408
4127001	Kawasan (B) Ulu Tekai	Jerantut	102.753	4.106	17,477					10,729					14,103
4219001	Bukit Betong	Lipis	101.940	4.233	17,494									11,763	14,628
* 4223115	Kg. Merting	Jerantut	102.383	4.243	13,225	13,293	14,740	17,596	10,899	9,789	10,283	11,914	8,616	11,552	12,191
4227001	Ulu Tekai (A)	Jerantut	102.733	4.233						9,950	10,276	6,081			8,769
4324001	Kuala Tahan	Jerantut	102.403	4.386	11,293	10,275	28,742	15,574	24,328	12,642					17,142
4513033	Gunong Brinchang di C.Highlands	C/Highlands	101.383	4.517		11,023	7,220	4,633	7,665		12,888	9,626	10,421	8,937	9,068
4620045	Paya Paloh	Lipis	102.008	4.678				15,290	11,667	9,595	19,034	18,283	16,733	15,088	15,100

note: EI_{30} marked in red font are considered outliers and not included in computation of R factor

Figure 4 Example of Computed annual EI_{30} for Johor.

Table 3 Summary of interpolation parameters using simple kriging

Parameter	Values
Value to be Interpolated	Average Annual EI_{30} (R Factor)
Semivariograms Properties: A. Kriging Method B. Semivariogram Model	 Ordinary Kriging Spherical
Interpolation cell size	5 x 5km
Kriging Parameter: • Search Type • Number of Points • Maximum Search Distance	 Fixed 15

Isoerodent map produced can be found in Figure 5 below. The map shows the rainfall erosivity distribution for the entire Peninsula Malaysia. The maps are also furnished with more location of major towns/ cities and gridlines to assists in locating the Erosivity R Factor for any potential site to be studied.

5.0 Result discussion & further improvements

The USLE has been around for several decades. While it contributes immensely for soil loss estimation worldwide, it is often disputed by researchers over the method of determining its factors, in particularly the R factor. Doubts of selection of I_{30} (Agnese et al, 2006; Yin et al, 2007), equation to determine unit energy (Van Dijk et al, 2002; Shamshad et al, 2008a), and other rainfall event selection criteria (Morgan, 1994; Uson and Ramos, 2001) are often debated by researchers and practitioners alike. It is not uncommon for USLE (or RUSLE) to be modified to suit local condition (for example, see Fornis et al, 2005). Nevertheless, USLE/RUSLE provides an effective tool 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 kriging 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.

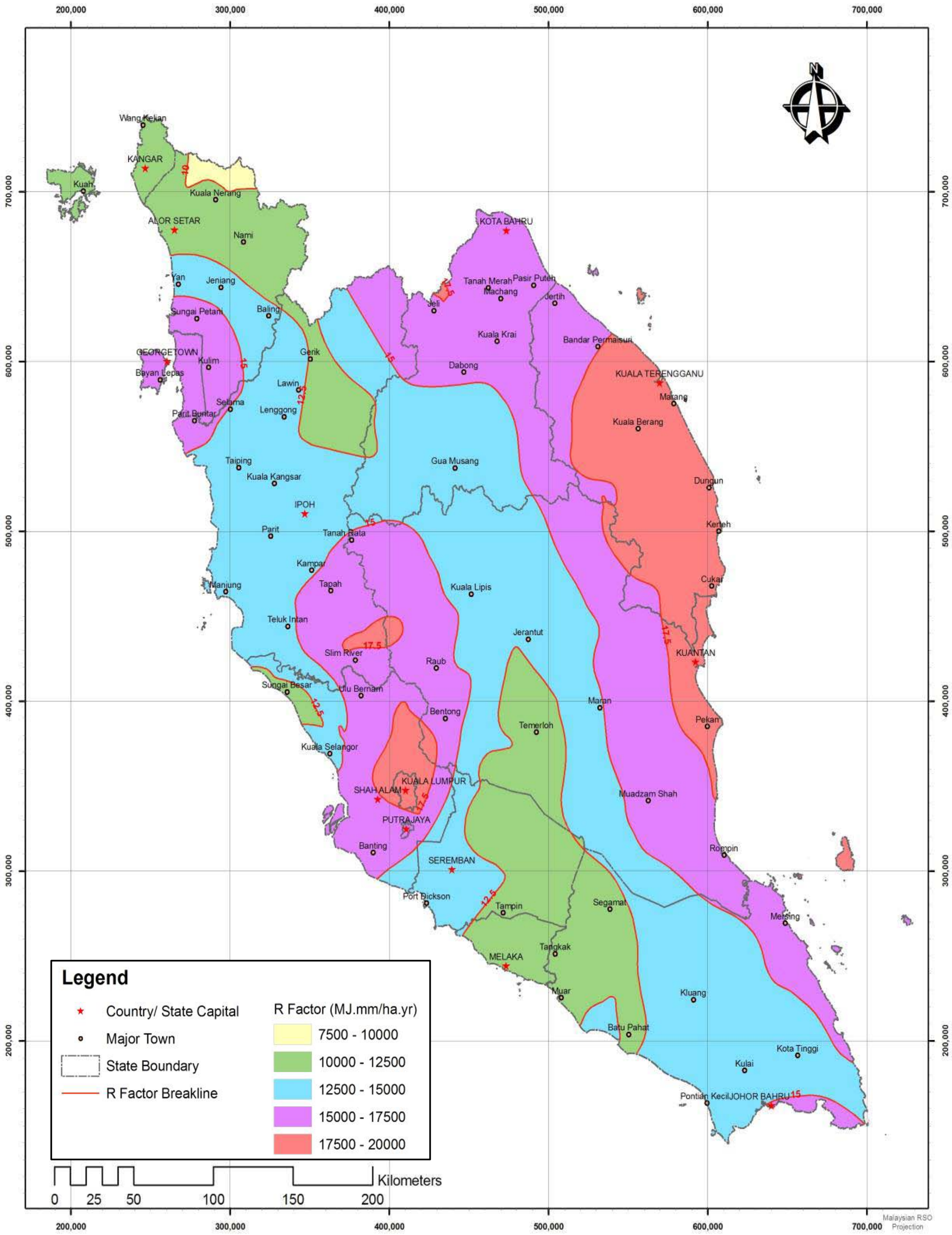

Figure 5 Rainfall erosivity map for Peninsular Malaysia

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 peninsular 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 EI_{30} 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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