A Comparison of the R-Factor in the Universal Soil Loss Equation and Revised Universal Soil Loss Equation

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Abstract. *The R-factor in the Universal Soil Loss Equation /Revised Universal Soil Loss Equation (USLE/RUSLE) characterizes the climatic influence on the average rate of soil loss. The way in which the R-factor was calculated for RUSLE differs from that for the USLE. Rainfall intensity data at 6-min intervals from 41 long-term sites in the tropical region of Australia were analyzed to determine the discrepancy in the calculated R-factor as a result of using different unit energy equations and different rainfall thresholds. The mean annual rainfall varies from 261 to 4030 mm for the 41 sites. The calculated R-factor using the unit energy equation for the USLE is greater than that using the unit energy equation recommended for RUSLE. The typical difference is about 10% for the tropical region of Australia. The difference tends to increase as peak rainfall intensity decreases. The percentage difference in the R-factor due to different unit energy equations was found to be significantly correlated with the ratio of the R-factor to mean annual rainfall. The discrepancy in the calculated R-factor due to different rainfall thresholds increases as mean annual rainfall decreases because the relative contribution to the R-factor from small storm events increases in low rainfall areas. Lowering the rainfall threshold from 12.7 mm to 0.0 mm would on average increase the calculated R-factor by 5% for the same region. Relationships based on mean annual rainfall and the R-factor were developed so that the magnitude of the discrepancy in the calculated R-factor due to different unit energy equations and different rainfall thresholds can be readily assessed.*

Keywords. *USLE, RUSLE, R-factor, tropics, Australia.*

At present the most commonly used method of predicting the average rate of soil loss due to water erosion, especially from agricultural lands, is the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and its successor the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997). In the USLE/RUSLE, the climatic influence on water-related soil erosion is characterized by a rainfall-runoff erosivity factor, known as the R-factor. By definition, the R-factor is the mean annual sum of individual storm erosivity values, EI_{30}, where E is the total storm kinetic energy and I_{30} is the maximum 30-min rainfall intensity. When factors other than rainfall are held constant, soil losses due to water erosion are directly proportional to the level of rainfall erosivity (Wischmeier and Smith, 1958, 1978).

Although the procedure to calculate the storm erosivity, hence the R-factor, is well defined (Renard et al., 1997), there are discrepancies in the way in which the R-factor is determined for individual regions. For example, for the eastern United States, the isoerodent map was prepared using the original unit energy equation (Wischmeier and Smith, 1978); while for the western United States, a different unit energy equation suggested by Brown and Foster (1987) was used (Renard et al., 1997), and this new unit energy equation was recommended for all future use in relation to RUSLE (Renard et al., 1997). Furthermore, a rainfall threshold of 12.7 mm was used to select erosive storms for the eastern United States, while all storms were used in calculating the R-factor for the western United States unless the precipitation occurred as snowfall (Renard et al., 1997). Although no systematic examination of the effects of using different unit energy equations and rainfall thresholds was undertaken, Agriculture Handbook 703 (Renard et al., 1997) seems to suggest that any difference in the calculated R-factor would be small since less than 1% difference in the total kinetic energy of some sample storms was cited (Renard et al., 1997). However, as shown later in this article, considerable difference in the calculated R-factor can occur as a result of using a different unit energy equation or a different rainfall threshold.

For convenience of discussion, the difference in the R-factor that results from using a different unit energy equation for computing storm energy is called the Type-I difference. The difference that arises from using a different rainfall threshold is called the Type-II difference. In particular, we are interested in the magnitude of the two percentage differences δ_1 and $\delta_2(R)$, and they are defined as follows:

$$\delta_1 = 100\frac{R_U - R_R}{R_R} \quad (1)$$

where R_U is the R-factor calculated using the unit energy equation of Wischmeier and Smith (1978) for the USLE and R_R is the R-factor calculated using the unit energy equation of Brown and Foster (1987) for RUSLE. A threshold of 12.7 mm is used for both R_U and R_R. $\delta_2(R)$ is similarly defined:

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$$\delta_2(R) = 100\frac{R_o - R_R}{R_R} \qquad (2)$$

where R_o is the R-factor calculated using a threshold of 0.0 mm and the unit energy equation of Brown and Foster (1987). Hence, the R-factor based on a threshold of 12.7 mm and the unit energy equation of Brown and Foster (1987) can be seen as a reference R-factor against which the effects of using different unit energy equations and different rainfall thresholds will be evaluated. For completeness, the Type-I difference using a threshold of 0.0 mm and the Type-II difference using the unit energy equation for the USLE are also considered.

In this article, an analytical relationship for the difference in storm energy is derived first for a simple storm pattern. Rainfall intensity data at 6-min intervals for 41 sites from the tropical region of Australia are then used to determine the differences in the calculated R-factor as a result of using different unit energy equations and rainfall thresholds. Finally, the differences are related to the R-factor and mean annual rainfall so that an assessment of the magnitude of the these differences can easily be made.

Data and Method of Analysis

All the pluviograph sites in Australia's tropics were screened to select those in operation for at least 20 years. Data used in this article include all the available 6-min pluviograph data from Bureau of Meteorology for 41 sites in the tropics of Australia. Table 1 shows the location, mean annual rainfall and the R-factor for the 41 sites. The R-factor was calculated in an identical manner as for the western United States, i.e., using the unit energy equation of Brown and Foster (1987) and all storm events. The mean annual rainfall for these sites ranges from 261 to 4030 mm/yr (10-159 in./yr), and the R-factor from 623 to 25,600 MJ·mm/(ha·h·yr). With a conversion factor of 17.02 (Foster et al., 1981), the range of the R-factor in U.S. customary units is 36.6 to 1,500. Calculated R-factors were then compiled for the 41 sites in order to evaluate the Type-I and Type-II differences. The mean annual rainfall and the R-factor were determined using the pluviograph data alone. More reliable estimates of the mean annual rainfall and the R-factor based on the long-term daily rainfall data in addition to pluviograph data for the 41 sites have been produced and are available elsewhere (Yu, 1998). Rainfall data from the tropical region were thought to be particularly suitable for evaluating the Type-I and Type-II differences in the R-factor because the range in rainfall intensity experienced in this region is greater than that in temperate regions.

Table 1. Location, mean annual rainfall, and R-factor for 41 sites in the Australian tropics

Station No. and Name	Location	Elevation (m)	Rain (mm/yr)	R-factor [MJ·mm/(ha·h·yr)]
02012 Halls Creek	18°14'S 127°40'E	410	575	2588
03003 Broome	17°57'S 122°14'E	17	605	3684
04032 Port Headland	20°22'S 118°37'E	9	364	1323
06011 Carnarvon	24°53'S 113°40'E	4	261	623
13017 Giles	25°02'S 128°18'E	580	302	787
14015 Darwin Airport	12°25'S 130°52'E	31	1688	13279
14400 Maningrida	12°03'S 134°13'E	11	1175	6997
14508 Gove Airport	12°17'S 136°49'E	54	1349	8148
14618 Daly Waters	16°16'S 133°23'E	212	896	4699
14626 Daly Waters AMO	16°16'S 133°23'E	220	628	2557
15085 Brunette Downs	18°39'S 135°57'E	218	547	2651
15135 Tennant Creek	19°38'S 134°11'E	375	445	2025
15548 Rabbit Flat	20°13'S 130°01'E	340	502	1995
15590 Alice Springs	23°49'S 133°54'E	537	323	917
15602 Jervois	22°57'S 136°09'E	325	352	1105
27006 Coen	13°46'S 143°07'E	162	1190	5839
27022 Thursday Island	10°35'S 142°13'E	60	1795	12985
28004 Palmerville	16°00'S 144°04'E	207	1027	6646
29041 Normanton	17°40'S 141°04'E	8	946	6447
29127 Mount Isa	20°40'S 139°29'E	343	448	2061
30045 Richmond	20°42'S 143°08'E	211	569	2483
31011 Cairns	16°53'S 145°45'E	3	1993	11589
31034 Kairi	17°12'S 145°34'E	715	1282	4735
31055 Mossman South	16°19'S 145°23'E	0	2120	11579
31066 Mareeba	17°00'S 145°25'E	406	870	3403
31083 Koombooloomba	17°50'S 145°36'E	732	2627	8908
32021 Goondi Mill	17°31'S 146°01'E	27	3220	15026
32040 Townsville	19°15'S 146°46'E	4	1101	5931
32042 Tully	17°56'S 146°56'E	24	4027	25578
32064 Paluma	19°00'S 146°12'E	892	2649	18369
33002 Ayr	19°37'S 147°22'E	12	998	5610
33119 Mackay	21°07'S 149°13'E	6	1665	10001
34002 Charters Towers	20°05'S 146°16'E	310	670	3217
35069 Tambo	24°53'S 146°15'E	395	516	1682
35098 Emerald	23°30'S 148°09'E	180	648	3299
36031 Longreach	23°26'S 144°17'E	192	455	1706
37051 Winton	22°24'S 143°02'E	185	465	1625
38003 Boulia	22°55'S 139°54'E	157	295	668
38024 Windorah	25°26'S 142°39'E	126	307	838
39083 Rockhampton	23°23'S 150°29'E	10	843	3116
39090 Theodore	24°57'S 150°04'E	142	699	2845

As part of a project to determine rainfall erosivity for Australia's tropics, a program, known as RECS, was written to compute EI_{30} for individual storms and ultimately the R-factor (Yu, 1998; Yu and Rosewell, 1998). Although the program strictly conforms to the recommendations from Agriculture Handbook 703 (Renard et al., 1997), users are allowed to choose, among other things, the unit energy equation to be used, and to specify the rainfall threshold to define erosive storm events. Users can select one of three unit energy equations. They are the original set of equations for the USLE (Wischmeier and Smith, 1978), that of Brown and Foster (1987) which was recommended for RUSLE (Renard et al., 1997) and that of Rosewell (1986) which is more appropriate for southeastern Australia. A rainfall threshold of 12.7 mm (0.5 in.) was commonly used to eliminate small storm events in the calculation of the R-factor. It was thought that storms with total rain less than 12.7 mm did not contribute significantly to the R-factor and soil erosion, and removal of these small events with a threshold of 12.7 mm greatly reduced the cost of analyzing rainfall data (Renard et al., 1997).

For each of the 41 tropical sites, the program RECS was run four times using the same pluviograph data but with a different unit energy equation or a different rainfall threshold. Only the unit energy equations for the USLE and RULSE and thresholds of 0.0 and 12.7 mm were considered in this article.

Results

An Analytical Relationship for the Difference in Storm Energy and Storm Erosivity

The R-factor is the mean annual sum of individual storm erosivity values. It follows that the Type-I difference in the R-factor should be related to the difference in storm erosivity for individual events. Since the unit energy equation has no effect on the peak 30-min intensity, the difference in storm erosivity, hence in the R-factor, is only related to the difference in storm energy. We derived an analytical relationship between peak rainfall intensity and storm energy for a simple storm pattern to gain insight into the Type-I difference and to show the actual differences in an analytical framework.

Consider a triangular storm with a peak intensity of I_p and a storm duration of T, the total rain, P_t, and total storm energy, E, are given by:

$$P_t = \int_0^T i\,dt = \frac{I_p T}{2} \qquad (3)$$

and

$$E = \int_0^T e(i)\,i\,dt = \frac{T}{I_p}\int_0^{I_p} e(i)\,i\,di \qquad (4)$$

where e(i) is the unit energy equation which defines the kinetic energy per unit rainfall depth as a function of the rainfall intensity i. The expressions for total rain and total energy, i.e., equations 3 and 4, hold for triangular storms irrespective of when the peak rainfall intensity occurs. equation 4 allows the storm energy to be determined analytically. For RUSLE, the unit energy equation is given by:

$$e(i) = e_o\left(1 - \alpha e^{-\frac{i}{i_o}}\right) \qquad (5)$$

where e_o = 0.29 MJ/ha/mm, α = 0.72, and i_o = 20 mm/h (Brown and Foster, 1987). The total storm energy for RULSE, E_R, is given by integrating equation 4:

$$E_R = P_t\, e_o\left\{1 - 2\alpha I^{-2}\left[1 - (1 + I)\,e^{-I}\right]\right\} \qquad (6)$$

where $I = I_p/i_o$. Equation 6 indicates that storm energy primarily depends on rainfall amount because the storm energy would only increase by a factor of 2 from $0.139P_t$ to $0.274P_t$ when the peak intensity is increased by a factor of 10 from 10 m/h to 100 mm/h.

For the USLE, the unit energy equation is given by:

$$e(i) = e_1\left[1 + \beta \ln(i)\right] \qquad \text{when } i \le 76 \text{ mm/h} \qquad (7a)$$

and

$$e(i) = e_2 \qquad \text{when } i > 76 \text{ mm/h} \qquad (7b)$$

where e_1 = 0.119 MJ/ha/mm, e_2 = 0.283 MJ/ha/mm, and β = 0.3186 (Wischmeier and Smith, 1978). Again integrating equation 4 yields the total storm energy for USLE, E_U, in the form:

$$E_U = P_t\, e_1\left[1 + \beta(\ln I_p - 0.5)\right] \qquad \text{when } I_p \le 76 \text{ mm/h} \qquad (8a)$$

and

$$E_U = P_t\left\{e_1\left(\frac{76}{I_p}\right)^2\left[1 + \beta(\ln 76 - 0.5)\right] + e_2\left[1 - \left(\frac{76}{I_p}\right)^2\right]\right\} \qquad \text{when } I_p > 76 \text{ mm/h} \qquad (8b)$$

The percentage difference in storm energy can therefore be expressed analytically. For example, when $I_p \le 76$ mm/h, we have:

$$\frac{E_U - E_R}{E_R} = \frac{e_1\left[1 + \beta(\ln I_p - 0.5)\right]}{e_o\left[1 - 2\alpha I^{-2}\left(1 - e^{-I} - Ie^{-I}\right)\right]} - 1 \qquad (9)$$

The difference in storm energy for $I_p > 76$ mm/h can be similarly expressed. Equation 9 shows that for triangular storm events, the percentage difference in storm energy is a function of peak rainfall intensity only, and independent of the rainfall amount. Although equation 9 is based on a crude assumption of triangular storms, it sets up an analytical framework in which the actual difference in storm energy can be presented. It is important to note that the percentage difference in storm energy is the same as that in storm erosivity.

Type-I Difference in the R-factor

The analytical relationship between peak rainfall intensity and percentage difference in storm energy is shown in figure 1. In the same graph, the peak 30-min rainfall intensity is plotted against the percentage difference in storm energy for 556 natural storms. These storms were randomly selected, representing about 1% of all storms recorded at these 41 sites. In general, storm energy calculated using the unit energy equation for the USLE is higher than that using the unit energy equation for RUSLE. The maximum difference of 40-50% occurs when the peak rainfall intensity is less than 10 mm/h. The difference then decreases as the peak rainfall intensity increases. Storm energy calculated using the unit energy equation for the USLE can be less than that calculated using the unit energy equation recommended for RUSLE when the peak rainfall intensity exceeds 50 to 60 mm/h. It can be seen from figure 1 that the relationship between the

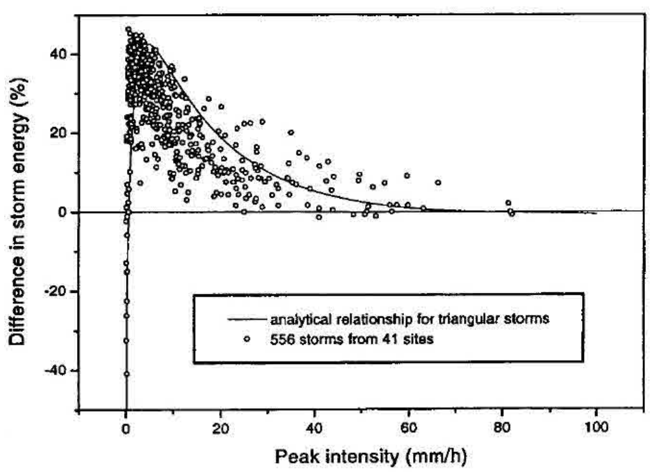

Figure 1–The relationship between the difference in storm energy and peak rainfall intensity.

actual difference in storm energy and the peak 30-min intensity for natural storms broadly follows the analytical relationship assuming a triangular storm pattern, although there is a considerable amount of scatter in figure 1. It is worth emphasizing that since the same peak 30-min intensity value is used to compute storm erosivity for individual events, the percentage difference in storm erosivity is identical to that in storm energy.

While the analytical relationship provides a guide as to the magnitude of the difference as a function of peak intensity for individual storm events, it is difficult to infer from the analytical relationship the percentage difference in the R-factor because the R-factor is the mean annual sum of all storm erosivity values. Storms with high peak intensity occur infrequently but can contribute a great deal to the R-factor. The difference in storm energy and storm erosivity for these events are relatively small as suggested by figure 1. Smaller storms are numerous and their contribution to the R-factor may be small while the difference in storm energy and storm erosivity for these small events is large. Thus the Type-I difference in the R-factor should be related to some weighted peak intensity for each site. For each of the 41 sites, a weighted average peak intensity is calculated as follows:

$$\bar{I}_p = \frac{\Sigma I_{30} E_R}{\Sigma E_R} \qquad (10)$$

where I_{30} is the peak 30-min rainfall intensity (in mm/h) and E_R is storm erosivity (in MJ/ha) calculated using the unit energy equation of Brown and Foster (1987). The summation is over all storm events for the site. Thus $\bar{I}_p$ can be seen as an average peak intensity weighted by the storm energy. In figure 2, the Type-I difference in the R-factor is plotted against this average peak intensity. The analytical relationship is also shown in figure 2 for comparison. For the 41 sites, the weighted average peak intensity varies from 32.5 to 45.1 mm/h, and the Type-I difference in the R-factor varies from 5.4% to 17% with an average of 9.4%. The relationship between the Type-I difference in the R-factor and the energy-weighted average peak intensity is broadly similar to the analytical relationship (fig. 2). This implies that the maximum Type-I difference in the R-factor under any circumstances would be no greater than about 40%, and as the average peak intensity decreases, the Type-I difference would tend to increase.

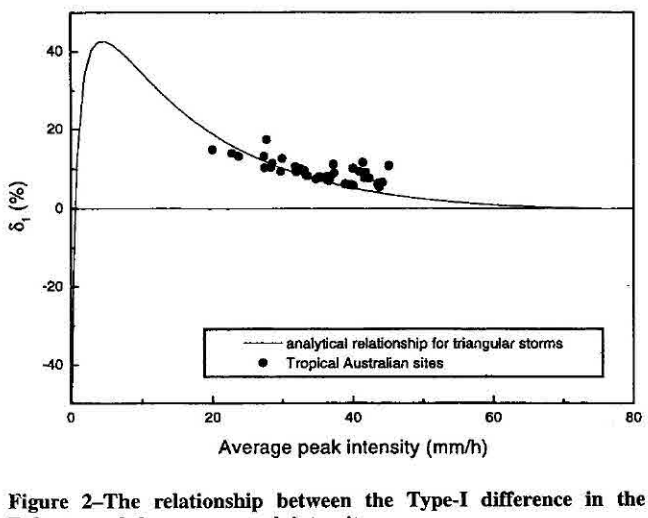

Figure 2–The relationship between the Type-I difference in the R-factor and the average peak intensity.

It follows from the definition of the R-factor that the numerator in equation 10 is related to the R-factor. The denominator is related to the mean annual rainfall because storm energy is primarily related to total storm rainfall. Equation 10 would therefore suggest that the average peak intensity should be related to the ratio of the R-factor to mean annual rainfall. Data for the 41 sites yield a good linear relationship:

$$\bar{I}_p = 16.4 + 4.09\frac{R_R}{P}, \qquad E_c = 0.89 \qquad (11)$$

where P is the mean annual rainfall in mm/yr and R_R in MJ·mm/(ha·h·yr). E_c is the coefficient of efficiency (Nash and Sutcliffe, 1970). E_c is the ratio of the unexplained to total variation in the dependent variable and is a powerful indicator of the model's performance. E_c is applicable to all predictive models and is identical to the commonly used r^2 for linear regression models. Given the positive relationship between the R_R to P ratio and the average peak intensity (eq. 11) and the negative relationship between the average peak intensity and the Type-I difference in the R-factor (fig. 2), a negative relationship between the Type-I difference in the R-factor and the R_R to P ratio is expected. For the 41 sites, an empirical relationship was developed:

$$\delta_1 = 14.9 - 1.21\frac{R_R}{P}, \qquad E_c = 0.43 \qquad (12)$$

The relationship (eq. 12) is not as good as that between the average peak intensity and R_R/P, but the correlation between δ_1 and R_R/P is significant at any practical level of interest. The relationship for the Type-I difference based on the R_R/P ratio would be more useful than that based on the average rainfall intensity as defined by equation 10 because the data on the R-factor and mean annual rainfall are more widely available than those on the average peak intensity. Figure 3 shows a scatter plot of the R_R to P ratio against the Type-I difference in the R-factor. The straight line in figure 3 represents the regression equation (eq. 12). The linear relationship between the R_R to P ratio and the Type-I difference in the R-factor should not be extrapolated beyond the observed range in R_R/P of 2.06 to 7.69 MJ/(ha·h), for the relationship is fundamentally non-linear as the analytical relationship suggests.

The Type-I difference considered so far is based on a threshold of 12.7 mm (eq. 1). When all storms were included, the Type-I difference in the R-factor increased slightly. The difference varies from 5.7% to 18% with an average of 10%. With the linear regression technique, the Type-I difference with all storms included was found to be 1.056 times larger than that when a threshold of 12.7 mm is used ($E_c > 0.99$).

Type-II Difference in the R-factor

For the Type-II difference in the R-factor, lowering the threshold from 12.7 mm would increase the number of

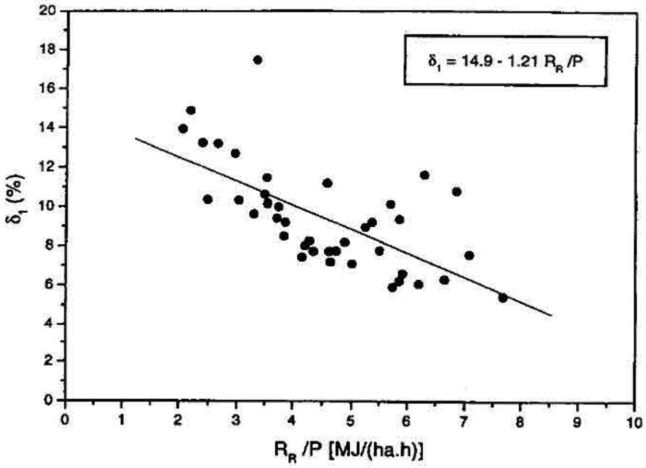

Figure 3–The relationship between the Type-I difference in the R-factor and the ratio of the R-factor to mean annual rainfall.

storms and increase the R-factor at a given site. In the low rainfall area, storms with total rain less than 12.7 mm would contribute a great deal more to the R-factor than in the relatively wet areas. It is therefore expected that the difference in the calculated R-factor due to different rainfall threshold would be more pronounced in areas of low rainfall. In figure 4, the percentage difference in the R-factor using 0 and 12.7 mm thresholds is plotted against the mean annual rainfall. The Type-II difference ranges from 1% to 10% with an average of 4.5%. It can be seen that the higher the mean annual rainfall the lower the Type-II difference in the calculated R-factor. Non-linear regression was used to fit a power function, resulting in:

$$\delta_2(R) = 482P^{-0.712}, \qquad E_c = 0.81 \qquad (13)$$

Equation 13 can be used to assess the magnitude of the Type-II difference, at least within the observed range of the mean annual rainfall for the 41 sites.

The Type-II difference in the R-factor using the unit energy equation for the USLE (Wischmeier and Smith, 19978) was also computed and related to the mean annual rainfall. The Type-II difference in the R-factor for the USLE is similar to that for RUSLE in magnitude with an average of 5.1% for the 41 sites. The regression equation based on data from the 41 sites is:

$$\delta_2(U) = 481P^{-0.694}, \qquad E_c = 0.81 \qquad (14)$$

The similarity between equation 13 and equation 14 is evident. Again with the linear regression technique, the Type-II difference for the USLE was found to be 1.113 times larger than that for RULSE ($E_c > 0.999$). Figure 5 show the Type-II difference in relation to the USLE and the regression equation based on the data from the 41 sites. In spite of the similarity in the Type-II difference between the USLE and RULSE, the results on the Type-II difference for the USLE are presented in figure 5 because this allows a comparison with the results of both Cooley et al. (1988) and McGregor et al. (1995) on the Type-II difference in relation to the USLE. Cooley et al. (1988) showed that when all storms were included to compute rainfall erosivity instead of using the 13 mm threshold, summer erosivity values were increased by 28 to 59% at the Reynolds Creek Experimental Watershed in southwestern Idaho. Data of McGregor et al. (1995) for Goodwin Creek Watershed in northern Mississippi showed an increase of 3.6% in the R-factor when the rainfall threshold was lowered from 13 mm to 0 mm. Figure 5 shows that equation 14 fits the data for Goodwin Creek Watershed very well. Figure 5 also shows that although both equation 14 and results of Cooley et al. (1988) suggest that the Type-II difference is very sensitive to total rainfall when the latter is low, equation 14 would have under-estimated the Type-II difference for the Reynolds Creek Watershed. The under-estimation occurs probably because in cold climates, rainfall is more likely to occur in smaller amounts in comparison to the tropics. This suggests that the likely bias

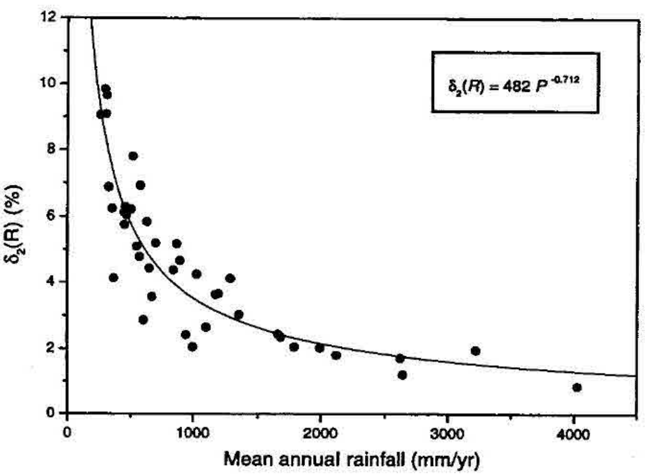

Figure 4–The relationship between the Type-II difference in the R-factor and mean annual rainfall. Unit energy equation of Brown and Foster (1987) for RUSLE was used.

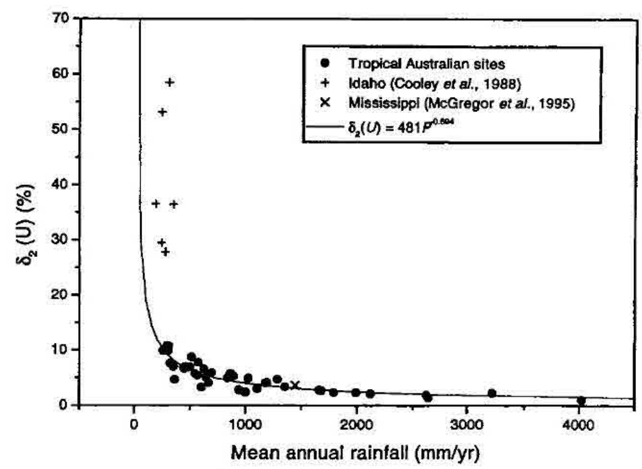

Figure 5–The relationship between the Type-II difference in the R-factor and mean annual rainfall. The unit energy equation of Wischmeier and Smith (1978) for the USLE was used. Results of Cooley et al. (1988) were based on total rainfall and rainfall erosivity for summer months. Summer months vary from February to November at low elevations, and from May to October at high elevations.

be taken into consideration when equation 13 and equation 14 are applied to the temperate regions.

Discussion and Conclusion

Of the six factors considered in the USLE/RUSLE, the R-factor is the most precisely defined. Uncertainties in other factors may be considerably greater than the magnitude of the differences in the R-factor identified in this article. These differences may even be smaller than the uncertainty in the calculated R-factor itself. The latter occurs because of the limited and often incomplete rainfall intensity data, and of the inherent climatic variability. Discrete representation of rainfall intensity at different time intervals also has noticeable effects on the computed R-factor values (Istok et al., 1986; Kramer, 1987). Although how significant these differences in the calculated R-factor can only be considered in relative terms, equations 12 and 13 can be readily used to assess the magnitude of the differences and to determine whether further consideration of this issue is warranted. More importantly, for a large number of investigations that have been undertaken to validate and apply the USLE around the world, equations 12 and 13 present simple ways to adjust the R-factor determined for the USLE without having to recalculate the R-factor for RUSLE applications.

In conclusion, the calculated R-factor using the unit energy equation for the USLE is in general greater than that using the unit energy equation recommended for RUSLE. The typical difference is about 10% for the tropical region of Australia. The difference tends to increase as peak rainfall intensity decreases, implying a greater discrepancy in the calculated R-factor in temperate regions. The discrepancy in the calculated R-factor due to different rainfall thresholds increases as mean annual rainfall decreases because the relative contribution of small storm events to the R-factor tends to increase in low rainfall areas. Lowering the rainfall threshold from 12.7 mm to 0.0 mm would on average increase the calculated R-factor by 5% for the same region.

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