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Using monthly precipitation data to estimate the R -factor in the revised USLE

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Abstract

The methods used to calculate both the Revised Universal Soil Loss Equation (RUSLE) erosivity factor (R) and the 10 year frequency storm erosion index value (EI_{10}) are presented. As the calculation methods require long-term rainfall intensity data, and such data are not available for all application sites, an approach used to estimate the R -factor is described. Examples illustrating applications of the estimation technique in Africa, Asia, and other parts of the world are summarized. The method, which establishes correlations between measured R -values and more readily available precipitation data, is used to develop relations for estimating R -values in the USA. Correlations based on average monthly precipitation data and the R -factor values for 155 US stations were initially used to develop estimation relations. The 155 stations were segregated based on the annual distribution of monthly precipitation and the correlations improved. Exclusion of 23 stations with both 'winter-type' precipitation distributions and modified Fournier index values greater than 100 mm improved the relations for the remaining 132 stations ($r^2 = 0.81$). An estimation relation for the EI_{10} is also presented. The R -factor and EI_{10} estimation relations should facilitate the use of RUSLE for locations with only monthly precipitation data.

1. Introduction

The Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1991), like its predecessor the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965, 1978), is an erosion model designed to predict the long-term average annual soil loss from specific field slopes in specified land-use and management systems (i.e. crops,

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rangeland, recreational areas). Wischmeier (1976) explained that the USLE was designed to guide the selection of conservation practices for specific sites, to estimate the possible reduction in soil loss if a conservation practice is adopted, to determine acceptable cropping intensity for alternative conservation measures, and to define maximum slope lengths that are acceptable for given cropping and management practices. The equation is not recommended for geographic regions where its factors cannot be accurately evaluated, for computing soil erosion from complex watersheds (by taking overall average slope length and making other adjustments), and for estimating soil erosion from specific rainfall events (Wischmeier, 1976).

The USLE quantifies soil erosion as the product of six factors representing rainfall and runoff erosivity (R), soil erodibility (K), slope length (L), slope steepness (S), cover and management practices (C), and supporting conservation practices (P). The equation is thus

$$A = R \times K \times L \times S \times C \times P \quad (1)$$

where A is the computed spatial and temporal average soil loss per unit of area. Only two of the six factors in the equation, the rainfall and runoff erosivity factor (R) and the soil erodibility factor (K), have units. The average annual soil loss per unit of area is expressed in the units selected for K and the period selected for R .

RUSLE utilizes the same basic equation but is a computerized version that incorporates the results of additional research and experience obtained since the 1978 publication of the USLE (Agriculture Handbook No. 537, Wischmeier and Smith, 1978). These improvements include: new, and in some cases, revised isoerodent maps to estimate the R -factor and 10 year frequency storm erosivity index (EI_{10}) for the US; a time-varying approach for the K -factor to reflect freeze–thaw conditions and consolidation caused by moisture extraction of a growing crop; a subfactor approach to evaluating the C -factor for cropland, rangeland, and disturbed areas; a new equation for the L - and S -factors which considers the ratio of rill to interrill erosion; and new conservation practice values (P) for cropland and rangeland.

Both USLE and RUSLE are empirical relationships and thus should normally be considered valid only within the range of experimental conditions from which they are derived. However, since the equation represents the major factors affecting erosion (Hudson, 1977; Foster and Meyer, 1977), transferring it to locations throughout the world requires only the determination of appropriate values for the different factors (Foster et al., 1982).

In the US, the soil erodibility, slope length, slope steepness, and the cover and management factors can be readily evaluated using methods described in the RUSLE documentation and user guide (Renard and Ferreira, 1993). Similarly, the R -factor and the P -factor for contour farming (the P -factor is adjusted in RUSLE based on the 10 year frequency storm EI_{10} -value to account for storm severity effects on contour farming) can be evaluated using, respectively, annual and 10 year isoerodent maps or by computation from long-term rainfall intensity data from the application site.

In contrast, lack of long-term rainfall intensity data in some countries makes applying the USLE, and eventually RUSLE, more difficult. Although site-specific

soil data, topographic maps or field surveys, and the CROPS and OPERATIONS database of RUSLE facilitate estimations of the K -, C , R and P -factors for crop and rangeland locations, the long-term precipitation intensity data needed to evaluate the R -factor and P -factor for contour farming are generally not as available. While the obstacle of estimating R -factor values for areas without sufficient data has existed since the introduction of USLE, the need to estimate 10 year frequency storm EI_{10} -values in data-poor regions of the world is a new challenge for RUSLE users.

Although there are six factors comprising the fundamental relation of USLE and RUSLE, the calculation and estimation of the R -factor and the EI_{10} are the focus of this paper.

2. Calculation of the R -factor and EI_{10}

Although the methods used to calculate the R -factor and EI_{10} are described by Wischmeier and Smith (1978) and in the RUSLE user guide (Renard et al., 1994), they are presented here in order to define fully the R -factor.

The R -factor is the sum of individual storm EI -values for a year averaged over long time periods (> 20 years) to accommodate apparent cyclical rainfall patterns. The EI term is an abbreviation for energy multiplied by the maximum intensity in 30 min.

The kinetic energy of a unit rainfall amount depends on the sizes and terminal velocities of its raindrops—both of which are related to rainfall intensity. The total storm energy depends on the intensities at which the rainfall occurred and the precipitation amount that occurred at each intensity (Wischmeier and Smith, 1978).

The intensities at which the rainfall occurred and the amount that occurred at each intensity can be calculated from recorded rainfall data. Analog traces of rainfall depth vs. time are examined and the rainfall depth and clock time registered whenever the slope of the pen line changes. These breakpoint rainfall data are processed to obtain rainfall intensity in millimeters per hour (mm h^{-1}) units for each increment.

Rainfall intensity for a particular increment of a rainfall event (i_r) is calculated using the relation

$$i_r = \frac{\Delta V_r}{\Delta t_r} \quad (2)$$

where Δt_r is the duration of the increment over which rainfall intensity is considered to be constant in hours (h), and ΔV_r is the depth of rain falling (mm) during the increment.

Rainfall energy per unit depth of rainfall (e_r) can be calculated using the relation

$$e_r = 0.29[1 - 0.72 \exp(-0.05i_r)] \quad (3)$$

where e_r has units of megajoules per hectare per millimeter of rain ($\text{MJ ha}^{-1} \text{mm}^{-1}$), and i_r is rainfall intensity (mm h^{-1}). Eq. (3) is a replacement for the relation presented in Agriculture Handbook No. 537 (Brown and Foster, 1987). The revised relation is recommended for calculating rainfall energy per unit depth because it is based on more data than the relation presented in Agriculture Handbook No. 537 and has a

better functional form at lower intensities. Comparison of the revised unit energy relation results with those of the relation presented in Agriculture Handbook No. 537 showed less than a 1% difference in the EI of some sample storms (Renard et al., 1994).

The total storm kinetic energy (E) is calculated using the relation

$$E = \sum_{r=1}^m e_r \Delta V_r \quad (4)$$

where e_r is the rainfall energy per unit depth of rainfall per unit area in megajoules per hectare per millimeter ($\text{MJ ha}^{-1} \text{mm}^{-1}$), and ΔV_r is the depth of rainfall in millimeters (mm) for the r th increment of the storm hyetograph which is divided into m parts—each part with essentially constant rainfall.

In order to calculate the erosion index (EI) value for a particular storm ($\text{MJ mm ha}^{-1} \text{h}^{-1}$), total storm kinetic energy (E) (MJ ha^{-1}) is multiplied by the maximum amount of rain falling within 30 consecutive minutes (I_{30}) expressed in millimeters per hour (mm h^{-1}) units.

The average annual rainfall and runoff erosivity factor (R) ($\text{MJ mm ha}^{-1} \text{h}^{-1} \text{year}^{-1}$), is the average of calculated EI -values. The R -factor is mathematically defined as

$$R = \frac{1}{n} \sum_{j=1}^n \left[\sum_{k=1}^m (E)_k (I_{30})_k \right]_j \quad (5)$$

where E is the total storm kinetic energy (MJ ha^{-1}), I_{30} is the maximum 30 min rainfall intensity (mm h^{-1}), j is an index of the number of years used to produce the average, k is an index of the number of storms in each year, n is the number of years used to obtain the average R , and m is the number of storms in each year.

The 10 year frequency storm erosion index (EI_{10}) is the EI -value calculated for a storm having a 10 year return frequency.

Any precipitation falling as snow has no meaning with respect to EI and is therefore not included in R -factor calculations.

For EI calculations, a break between storms is defined as 6 h or more with less than 1.3 mm of precipitation. Rains less than 13 mm, and separated from other storms by 6 or more hours, are omitted as insignificant unless the maximum 15 min intensity exceeds 24 mm h^{-1} (Wischmeier and Smith, 1978).

The rainfall and runoff erosivity values of different locations can be plotted on a map and lines drawn between locations with equal rainfall and runoff erosivity. The lines, called isoerodent lines, can be used to estimate erosivity values for locations without calculated R -factor values. Linear interpolation can be used to estimate erosivity values for locations between the isoerodent lines. The R -factor and the EI_{10} isoerodent maps for California (USA), in US customary units of hundreds of

foot tonf inch acre⁻¹ h⁻¹ year⁻¹, are presented in Figs. 1 and 2 as examples of isoerodent maps.

3. Metric conversion of the *R*-factor and *EI*₁₀ units

The methods used to convert the *R*-factor and *EI*₁₀ terms from metric to US customary units, which have been well described by Foster et al. (1981), are presented here to clarify the application of Eq. (1).

Since the International System of Units (SI) is used throughout the world, and the current version of RUSLE requires values in US customary units (the release of a metric version of RUSLE is planned), attention must be given to the units used. The metric *EI* units of MJ mm ha⁻¹ h⁻¹ year⁻¹ should be divided by 17.02 to convert to US customary units of hundreds of foot tonf inch acre⁻¹ h⁻¹ year⁻¹ (Foster et al., 1981).

In the metric expression for *EI*, a megajoule can be expressed as a megameter Newton (Mm N). This form allows the megameter millimeter (Mm mm) product of the numerator, which is equivalent to 10 000 square meters (m²), to cancel the hectare term in the denominator. The resulting units, Newtons per hour per year (N h⁻¹ year⁻¹), should be divided by 1.702 to obtain US customary units of hundreds of foot tonf inch acre⁻¹ h⁻¹ year⁻¹ (Foster et al., 1981).

Although units of N h⁻¹ year⁻¹ are easier to write than either MJ mm ha⁻¹ h⁻¹ year⁻¹ or hundreds of foot tonf inch acre⁻¹ h⁻¹ year⁻¹, there are at least two disadvantages of using the N h⁻¹ year⁻¹ expression. First, since the magnitude of the *R*-factor expressed as N h⁻¹ year⁻¹ is similar to the magnitude of the *R*-factor expressed in hundreds of foot tonf inch acre⁻¹ h⁻¹ year⁻¹, confusion as to whether the value is in metric or US customary units could result. Secondly, it is not obvious from the units that *EI* is the product of energy and intensity (Foster et al., 1981).

Similarly, there are at least two disadvantages of using MJ mm ha⁻¹ h⁻¹ year⁻¹ units. For example, *R*-factor values in MJ mm ha⁻¹ h⁻¹ year⁻¹ units are approximately 17 times larger than *R*-factor values expressed in hundreds of foot tonf inch acre⁻¹ h⁻¹ year⁻¹ units. The resultant four or five digit numbers are more difficult to visualize and compare mentally than the smaller numbers characteristic of the *R*-factor expressed in US customary units (Wischmeier and Smith, 1981). In addition, the larger *R*-factor value would result in very small values for the soil erodibility factor (*K*). The *K*-factor, in metric units of t ha h ha⁻¹ MJ⁻¹ mm⁻¹, would range downward from a maximum of about 0.09 (Wischmeier and Smith, 1981). Wischmeier and Smith (1981) warned that absolute differences between *K*-factor values would be small enough that users of Eq. (1) could neglect important soil differences as insignificant.

Although there are good arguments for and against each of the metric expressions of the *R*-factor units, the MJ mm ha⁻¹ h⁻¹ year⁻¹ units will be used throughout this presentation. These units were selected primarily because they reduce possible confusion as to whether *R*-factor values are in metric or US customary units. When

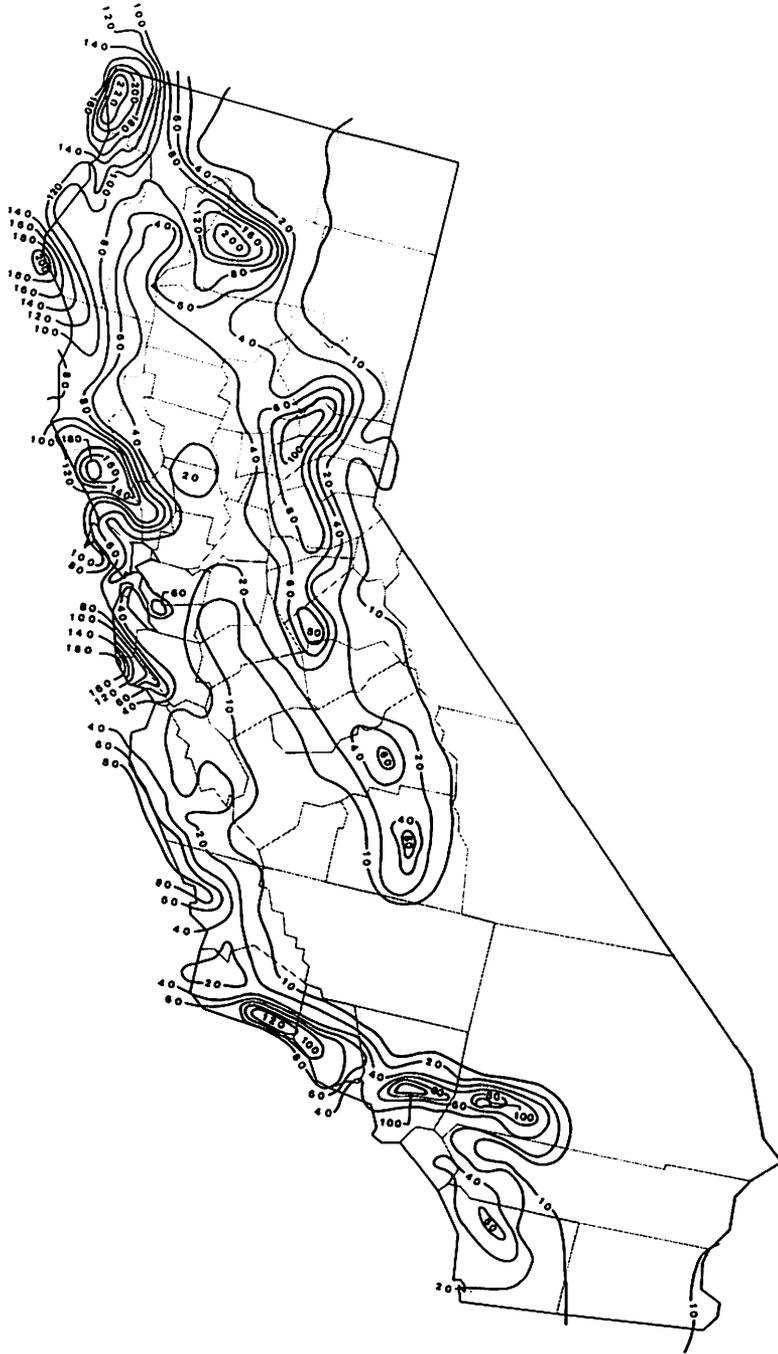


Fig. 1. Example R-factor isocrode map for California (hundreds of foot tonf inch acre⁻¹ h⁻¹ year⁻¹).

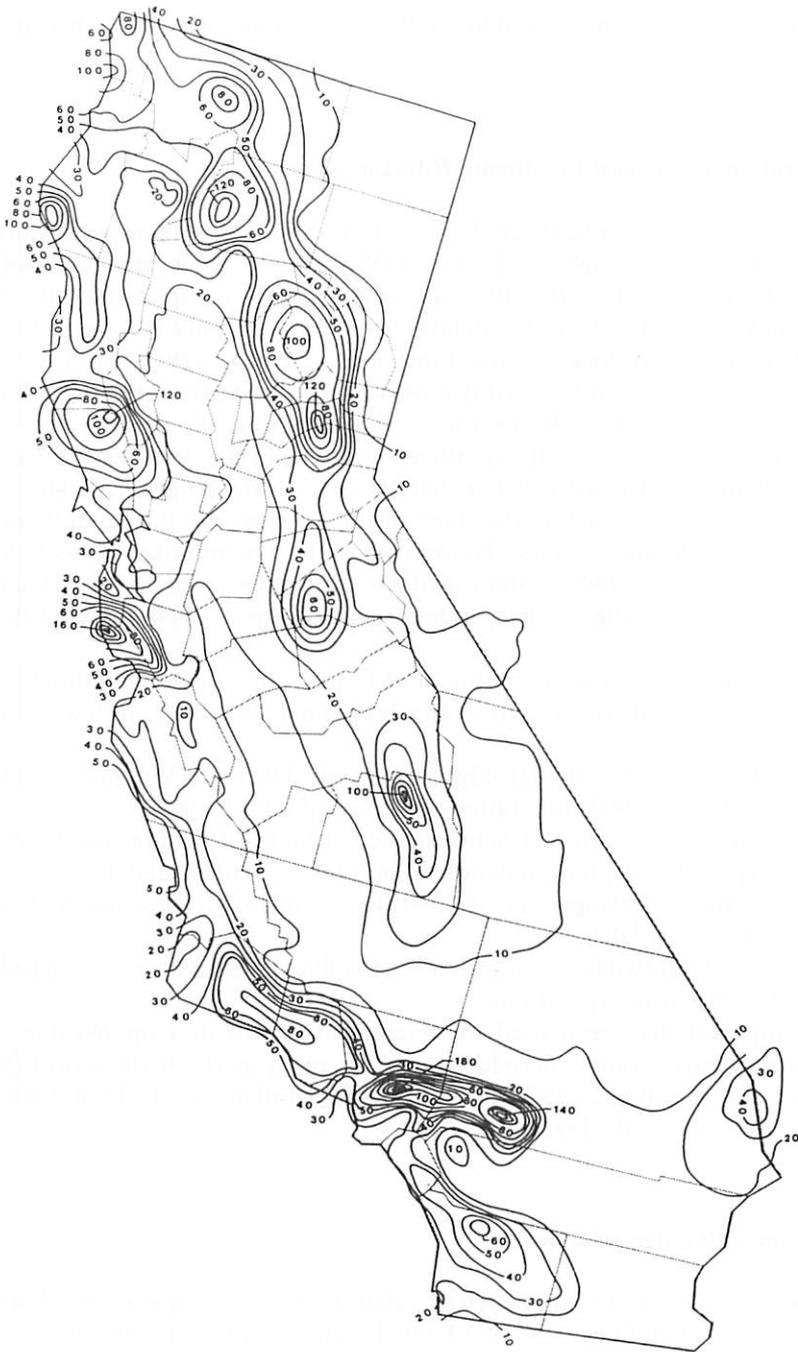


Fig. 2. Example EI_{10} isocroderent map for California (hundreds of foot tonf inch acre⁻¹ h⁻¹).

multiplied by the soil erodibility factor (K) expressed in $\text{t ha h ha}^{-1} \text{ MJ}^{-1} \text{ mm}^{-1}$, Eq. (1) solves for average annual soil loss (A) in units of metric tons per hectare ($\text{t ha}^{-1} \text{ year}^{-1}$).

4. General approach used to estimate R -factor values

Although the R -factor has been shown to be the index most highly correlated to soil loss at many sites throughout the world (Wischmeier, 1959; Stocking and Elwell, 1973; Wischmeier and Smith, 1978; Lo et al., 1985), several alternative erosivity indexes have been shown in the literature to be more highly correlated to soil loss for particular scales or locations (i.e. Fournier's p^2/P index (1960), Hudson's $KE > 1$ index (1971), Lal's AI_m index (1976)), and Onchev's P/St universal index (1985)). The work of these scientists indicates that an erosivity variable may be dependent on geographical area, scale, local conditions, and type of measurement and that there is no single universal variable better than the others (Stocking, 1987). The soil erodibility factor (K) is defined as the slope of the line between the rainfall and runoff erosivity factor (R) and soil loss (A) corrected by the dimensionless terms L , S , C , and P . Unless new soil erodibility values are defined for a new erosivity index, the R -factor (rather than a substitute erosivity index) should be used when applying the USLE (Foster et al., 1982).

The general approach used to estimate R -factor values for areas without data and/or resources required to calculate R can be summarized as the following four-step process:

- (1) R -factor values are calculated by the prescribed method (Wischmeier and Smith, 1978; Renard et al., 1993) for stations with recording rain gages;
- (2) a relation is established between the calculated R -values and more readily available types of precipitation data (i.e. monthly or annual totals);
- (3) the relation is extrapolated and R -values estimated for stations with the associated precipitation data;
- (4) isolines are drawn between stations— R -values for sites between isoerodents are estimated by linear interpolation.

This approach has been used by several authors to develop R -value selection guidelines or provisional isoerodent maps for many parts of the world (Stocking and Elwell, 1976a; Roose, 1977; Arnoldus, 1977; Bollinne et al., 1980; Smithen and Schulze, 1982; Lo et al., 1985).

5. R -factor estimation relations

Examples of guidelines and derived relations used to estimate the R -factor for locations other than the continental United States are presented below.

Working in West Africa, Roose (1977) reported a simple relation between the average annual R in units of hundreds of foot tonf inch $\text{acre}^{-1} \text{ h}^{-1} \text{ year}^{-1}$ and the

average annual rainfall in millimeters (P) over the 5–10 year period where recording rain gage records were available. The relation:

$$R = [(0.5 \pm 0.05)P] \quad (6)$$

was found to work for 20 meteorological stations in Ivory Coast, Burkina Faso, Senegal, Niger, Chad, Cameroon, and Madagascar. It was not valid for stations in mountainous regions, for stations directly on the coast, or for stations in the tropical transition zones between unimodal and bimodal annual rainfall distributions (Roose, 1977).

Based on the relation established for the 5–10 year periods of record, Roose used long-term annual precipitation records (20–50 years) to estimate average annual R -values. These values were used to develop an isoerodent map (in hundreds of foot tonf inch acre⁻¹ h⁻¹ year⁻¹ units) for West Africa south of Nouakchott, Mauritania and west of Sudan. Working in Rhodesia, Stocking and Elwell (1976a) observed a good relation between mean annual rainfall and mean annual R -values (Van der Poel, 1980). Given only mean annual rainfall data, they recommended the following R -values

Mean annual rainfall (mm)	R -factor (MJ mm ha ⁻¹ h ⁻¹ year ⁻¹)
300–400	–
400–500	1630
500–600	2000
600–700	2400
700–800	2800

The data suggest a 400 MJ mm ha⁻¹ h⁻¹ year⁻¹ change in the R -factor value for every 100 mm precipitation increment.

Working in Morocco, Arnoldus (1977) determined that Fournier's (1960) p^2/P index (where p is the average rainfall of the month with the highest rainfall and P is the annual average rainfall) was poorly correlated ($r^2 = 0.55$) with R -factor values at 178 stations (164 US stations and 14 West Africa stations). Arnoldus (1977) modified Fournier's index to

$$F = \frac{\sum_{i=1}^{12} p_i^2}{P} \quad (7)$$

where F is the modified index value, p_i is average monthly precipitation, and P is average annual precipitation. Using the same data set but with the modified Fournier index as the independent variable, Arnoldus (1977) obtained a much improved relation ($r^2 = 0.83$).

The improved relation was attributed to the characteristics of the two indices. Similar to the calculated R -factor, the modified Fournier index (F) increases with increasing rainfall. In contrast, the denominator of the original Fournier Index (p^2/P) increases with increasing rainfall in the months other than the highest rainfall month. As a result, the Fournier index can decrease with increasing rainfall—particularly if the rainfall is relatively uniformly distributed throughout the year (Arnoldus, 1977).

After subdividing the data set based on climate and obtaining different regression equations for each zone, Arnoldus concluded that relations obtained using the modified Fournier index should be applied only to locations within homogeneous climatic regions.

Following his work in Morocco, Arnoldus partitioned Africa and the Middle East into climatic zones based on the ratio of annual rainfall to potential evapotranspiration. He then used the modified Fournier index to create an isoerodent map in metric units for Africa north of the equator and the Middle East (FAO/UNEP/UNESCO, 1979; Arnoldus, 1980). In humid areas where there were not sufficient stations with calculated R -values, relations used in the less humid parts were extrapolated. Similarly, a relationship from the Sebou basin in Morocco was extrapolated to the drier parts of Africa (Arnoldus, 1980).

The following relation was used to develop an isoerodent map for Morocco (Arnoldus, 1977)

$$R\text{-factor} = 0.264F^{1.50} \quad (8)$$

where precipitation used to calculate F (see Eq. 7) is in millimeters and the R -factor is presumably in units of metric ton-meters centimeter per hectare per hour per year ($\text{t-m cm ha}^{-1} \text{ h}^{-1} \text{ year}^{-1}$).

The R -factor metric units used by Arnoldus in both his work in Morocco and in North Africa and the Middle East were identified as metric units but not specified. However, since units of $\text{t-m cm ha}^{-1} \text{ h}^{-1} \text{ year}^{-1}$ for the R -factor were presented in Agricultural Handbook No. 537 (Wischmeier and Smith, 1978), these were the units presumably used. A factor of 1.735 to convert from US customary to metric units is given for Morocco (Arnoldus, 1977) and a rounded 1.74 given for Africa and the Middle East (Arnoldus, 1980). In both cases, the conversion factor is different from the 1.702 presented by Foster et al. (1981).

The R -factor metric units presented in Agricultural Handbook No. 537 ($\text{t-m cm ha}^{-1} \text{ h}^{-1} \text{ year}^{-1}$) were corrected to units of $\text{MJ cm ha}^{-1} \text{ h}^{-1} \text{ year}^{-1}$ in the Supplement to Agricultural Handbook No. 537 (Wischmeier and Smith, 1981). In the initial release of Agricultural Handbook No. 537 (1978), the US customary unit for force (tonf) was mistakenly converted to metric units of metric ton (a mass unit) rather than the SI unit for force (Newton) (Foster et al., 1981).

In South Africa, Smithen and Schulze (1982) divided the country into homogeneous climatic zones, established relations between the calculated R -values at 13 key stations and one of four possible indices (total rainfall, effective rainfall, modified Fournier index, and a burst factor), extrapolated the relations developed for the key stations to 403 daily rainfall stations throughout the country, and created annual and 25 year return period isoerodent maps.

The Burst Factor (BF) was defined by Smithen and Schulze (1982) as

$$BF = \sum_{i=1}^{12} \frac{M_i Pe_i}{P} \quad (9)$$

where M_i is maximum daily rainfall for month i (mm), Pe_i is effective rainfall for

month i (mm), and P is annual rainfall (mm). Effective rainfall was defined as rainfall other than individual events that would be excluded if EI were being calculated from rainfall intensity data.

Lo et al. (1985) established that the R -factor was a valid erosivity index for Hawaii and, after examining both Fournier's index and the modified Fournier index, chose average annual rainfall as the best estimator of average annual R . Up to 90% of the total spatial variation in the R -factor could be explained by variations in mean annual rainfall (P). The equation is the following

$$R\text{-factor} = 38.46 + 3.48P \quad (10)$$

where R is in hundreds of Newtons per hour and P is in millimeters (Lo et al., 1985).

In summarizing soil erosion work in tropical regions, Lal (1990) notes that isoerodent maps have also been constructed for Sri Lanka (Joshua, 1977), India (Babu et al., 1978), Zimbabwe (Stocking and Elwell, 1976b), Kenya (Barber et al., 1981), and Malaysia (Maene et al., 1977). In addition, Chaves and Diniz (1981) presented calculated R -factor values for 10 stations in Brazil, Cooley et al. (1991) developed R -factor values for 10 Pacific Basin islands, and Pihan (1979) contributed an isoerodent map of France (Morgan, 1986).

Although the most accurate estimate of R -values can only be obtained from long-term rainfall intensity data as calculated by Wischmeier, the above work suggests that monthly precipitation data can give reasonable estimates of R -values for many regions throughout the world. However, as illustrated by differences in the isoerodent maps prepared for West Africa by Roose (1977) and by Arnoldus (1980), the estimation method used makes a difference to the R -value obtained. In addition, as illustrated by the different relations between annual average rainfall and R -values reported by Stocking and Elwell (1976a), Roose (1977), and Lo et al. (1985), the estimation relations can be location specific.

6. R -factor estimation relations for the continental United States

In the US, several authors have proposed methods for estimating R -values for stations without long-term rainfall intensity data or the resources to calculate directly the R -factor (Ateshian, 1974; Wischmeier, 1974; Cooley, 1980; Simanton and Renard, 1982). Although the methods, which are based on the 2 year frequency 6 h rainfall amount, predicted R -values with reasonable accuracy for the regions from which they were developed, some have met with limited success in other locations (Renard, 1975; Renard and Simanton, 1975; Simanton and Renard, 1982; Renard et al., 1994). Regardless of their effectiveness, these methods require data which are also generally not available worldwide and thus are not considered further in this paper.

Using the CITY database of RUSLE and isoerodent maps presented in the model documentation (Renard et al., 1993), R -factor and EI_{10} -values were identified for 155 stations in the continental US. The regression approach applied in other locations

throughout the world was used to relate R -values to annual average precipitation and the modified Fournier index as defined in Eq. (7). Monthly precipitation data (mm), averaged over the 1951–1980 period, were used to obtain average annual precipitation and modified Fournier index values for the 155 stations. Eight stations from the CITY database of RUSLE in Eastern Washington, Northeastern Oregon, and Idaho were excluded from the analysis because of the unique problems associated with rain and melting snow on partially thawed soil (McCool and Papendick, 1976).

When all 155 stations were considered, neither average annual precipitation or the modified Fournier index correlated well with R -values ($r^2 = 0.41$ and 0.29 , respectively). Since much higher coefficients of determination had been obtained by other authors, an attempt was made to segregate the stations into homogeneous climate zones. Stations were grouped by geographic location (coastal vs. inland stations) but correlations were not greatly improved. Although correlations were not greatly improved by this segregation, the correlations were better for inland locations than for those on the coast.

Because of the limited success delineating homogeneous climate zones based on geographic location, an attempt was made to segregate the stations based on the monthly distribution of annual precipitation. Examination of the monthly precipitation distributions of the 155 stations revealed three apparent annual distributions. The 155 stations were subsequently grouped into three subsets defined as:

- (1) no month with more than 15% of average annual precipitation ($n = 83$);
- (2) minimum of one summer month (May–September) with more than 15% of the annual average precipitation ($n = 37$);
- (3) minimum of one winter month (October–April) with more than 15% of the annual average precipitation ($n = 35$).

The correlations between the two indices (i.e. average annual precipitation and the modified Fournier index) and the R -factor value improved considerably for the first two subsets when compared with the unsegregated data set. In contrast, the correlations did not improve for the third subset. For stations with a more uniform annual precipitation distribution (subset 1), coefficients of determination improved from 0.41 and 0.29 for the unsegregated data set to 0.80 and 0.83 for the respective indices in the subset. For stations dominated by summer precipitation (subset 2), coefficients of determination improved, respectively, to 0.91 and 0.89. In contrast, coefficients of determination for stations dominated by winter precipitation (subset 3) were 0.23 and 0.31 for the indices. The poor correlations obtained for the winter-type precipitation distribution can be partially explained by the methods used to calculate R . As noted previously, any precipitation falling as snow has no meaning with respect to EI and is therefore not included in R -factor calculations.

Graphical analysis indicated that the outlier stations in the US data set ($n = 155$) were characterized as those with both winter-type precipitation distributions (subset 3) and with modified Fournier index values greater than 100 mm. These stations had high average annual precipitation totals (> 800 mm) and low R -values (< 1700 MJ mm ha⁻¹ h⁻¹ year⁻¹). When the 23 stations meeting these criteria were excluded from the analysis (mountain locations and stations in western Washington, western

Oregon, and northwestern California), the coefficient of determination for the US data set ($n = 132$) improved to 0.81 for both indices.

The data from the 132 stations can be characterized as having average annual precipitation ranging from 67 to 1640 mm, modified Fournier index values ranging from 7 to 150 mm, R -factor values ranging from 85 to 11 900 MJ mm ha⁻¹ h⁻¹ year⁻¹, and EI_{10} -values ranging from 85 to 3400 MJ mm ha⁻¹ h⁻¹.

A power function gave the highest coefficient of determination when compared with six other simple regression analyses of the R -factor (MJ mm ha⁻¹ h⁻¹ year⁻¹) versus either mean annual precipitation (P) or the modified Fournier index (F). However, graphical analysis indicates that the best-fit lines of the two power functions tend to underestimate R -factor values at higher values of the independent variables (Figs. 3(a) and 4(a)). As the parameter fit appeared to be dominated by the large number of data points with low R -factor values, a polynomial fit was attempted. The polynomial fits had lower coefficients of determination (and higher standard errors of estimation) than the power function but fit the data better at higher values of the independent variable (Figs. 3(b) and 4(b)).

The regression equations obtained with mean annual precipitation (P) (mm) and the R -factor (MJ mm ha⁻¹ h⁻¹ year⁻¹) ($n = 132$), are the following (Figs. 3(a) and (b))

$$R\text{-factor} = 0.04830P^{1.610} \quad (11)$$

and

$$R\text{-factor} = 587.8 - 1.219P + 0.004105P^2 \quad (12)$$

Eq. (11) has a 0.81 coefficient of determination and a 1075 standard error of estimation whereas Eq. (12) has a 0.73 coefficient of determination and a 1308 standard error of estimation.

Since each of the relations have limitations in predicting R -factor values, a composite relation may be considered. It is suggested that Eq. (11) be used for locations with mean annual precipitation less than 850 mm and Eq. (12) be used for locations with mean annual precipitation greater than 850 mm. The 850 mm threshold was selected because it precludes a large discontinuity if the composite R -values are plotted.

Similarly, the regression equations obtained with the modified Fournier index (F) (mm) and the R -factor (MJ mm ha⁻¹ h⁻¹ year⁻¹) ($n = 132$), are the following (Figs. 4(a) and (b))

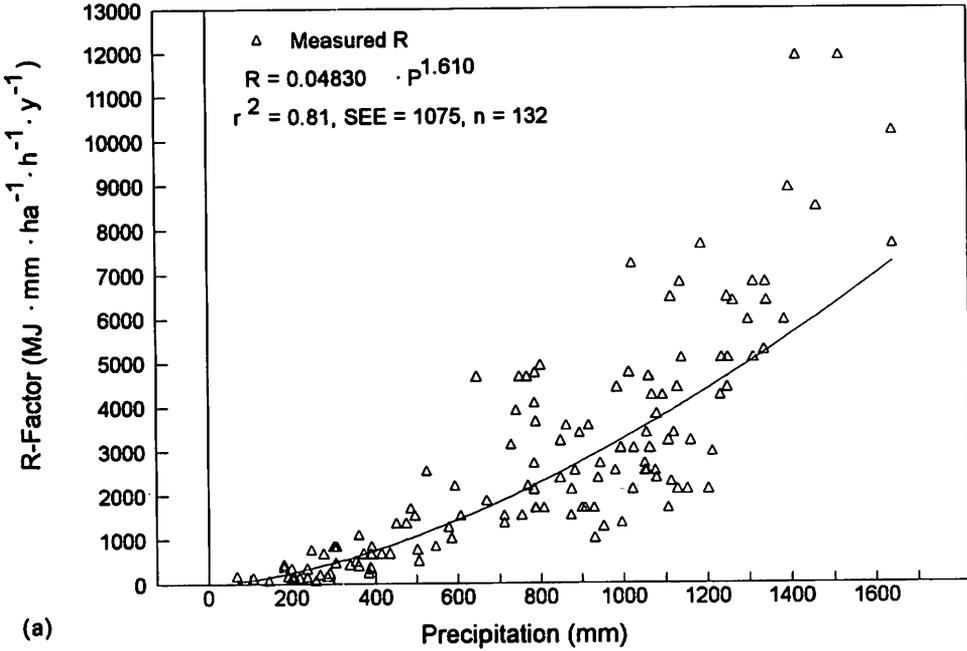
$$R\text{-factor} = 0.07397F^{1.847} \quad (13)$$

and

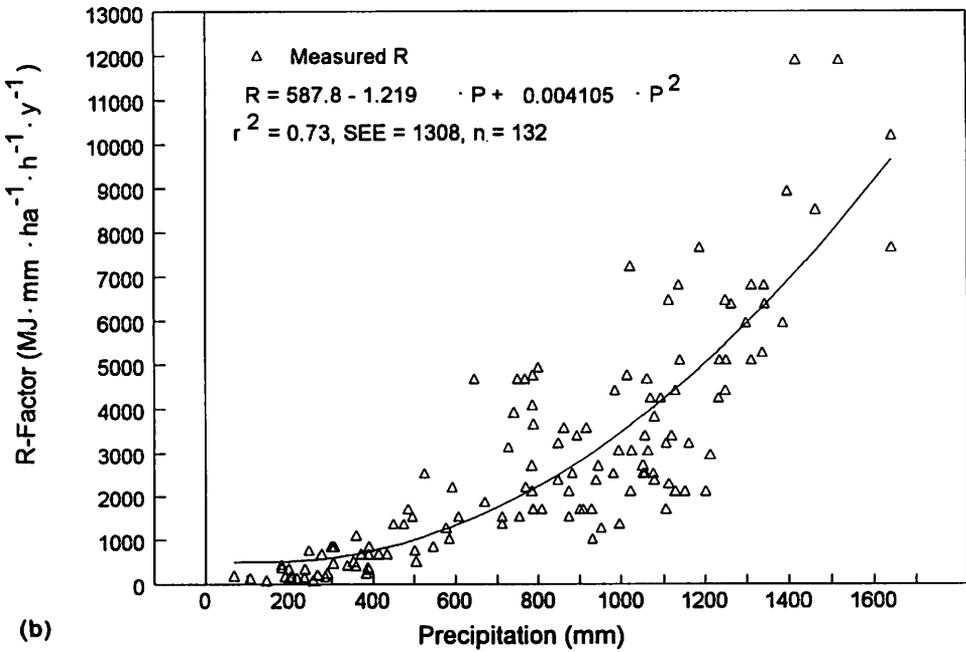
$$R\text{-factor} = 95.77 - 6.081F + 0.4770F^2 \quad (14)$$

Eq. (13) has a 0.81 coefficient of determination and a 1083 standard error of estimation whereas Eq. (14) has a 0.75 coefficient of determination and a 1237 standard error of estimation.

Similar to the relations developed using mean annual precipitation, a composite relation could provide the best fit over the range of modified Fournier index values. If



(a)



(b)

Fig. 3. (a) R-factor estimation relation based on average annual precipitation. (b) R-factor estimation relation based on average annual precipitation.

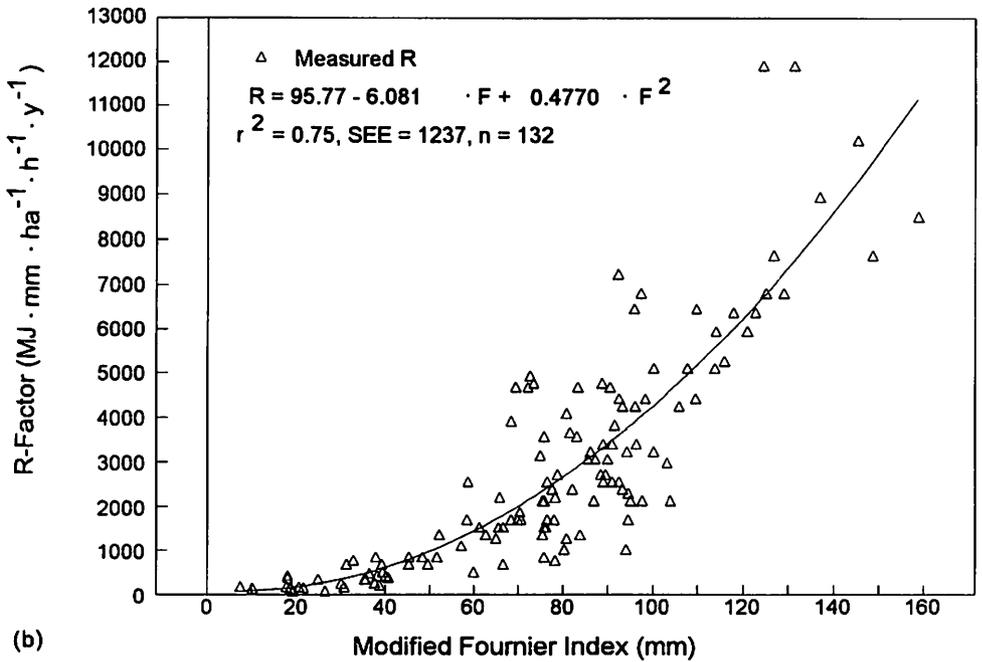
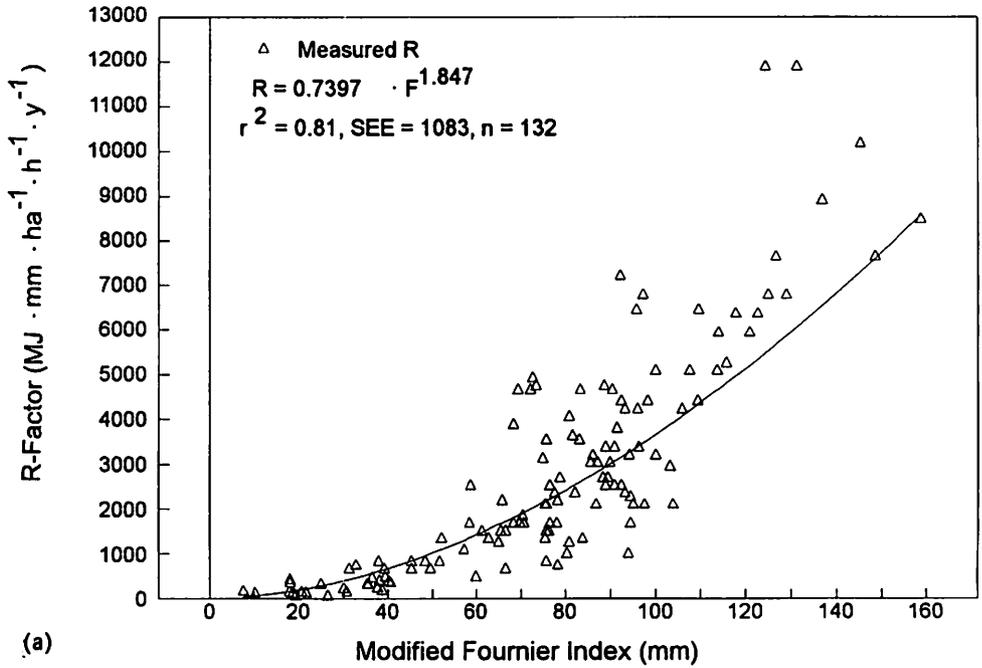


Fig. 4. (a) R-factor estimation relation based on modified Fournier index. (b) R-factor estimation relation based on modified Fournier index.

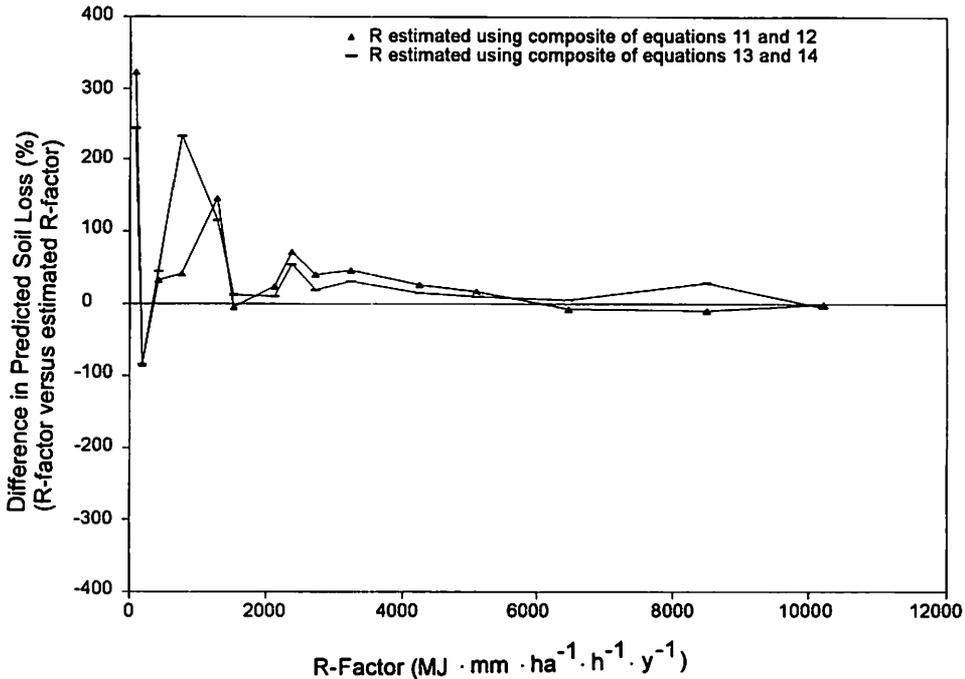


Fig. 5. Impact of potential R -factor estimation errors on predicted soil loss.

a composite relation is used, it is suggested that Eq. (13) be applied for locations with modified Fournier index values less than 55 mm and Eq. (14) be used for locations with modified Fournier index values greater than 55 mm.

In order to illustrate the impact of the potential errors in the estimation relations on predicted soil loss, the composite of Eqs. (11) and (12) described previously, as well as the composite of Eqs. (13) and (14), were used to estimate R -values for a range of US climatic zones. Holding representative values for the other RUSLE factors (i.e. K , L , S , C , P) constant, soil loss was predicted using identified R -factors and the two estimated R -values. The resulting percentage differences in soil loss predicted using the identified R -values versus the estimated R -values are shown in Fig. 5.

Fig. 5 suggests that R -factor estimation errors can have large effects on predicted soil loss but the effects tend to decrease with increasing R -values. For example, at the site with a R -value of 85 $\text{MJ mm ha}^{-1} \text{ h}^{-1} \text{ year}^{-1}$, Eqs. (11) and (13) estimated R -values that resulted in, respectively, 322% and 244% higher predicted soil loss than predicted using the identified R -value. In contrast, at the site with a 8510 $\text{MJ mm ha}^{-1} \text{ h}^{-1} \text{ year}^{-1}$ R -value, Eqs. (12) and (14) estimated R -values that resulted in, respectively, 14% and 9.3% higher predicted average annual soil losses. This effect is expected since as the R -factor increases, the relative magnitude of the standard error of estimation decreases.

In a sensitivity analysis of the RUSLE database, Renard and Ferreira (1993) demonstrated that the response in the predicted average annual soil loss, resulting

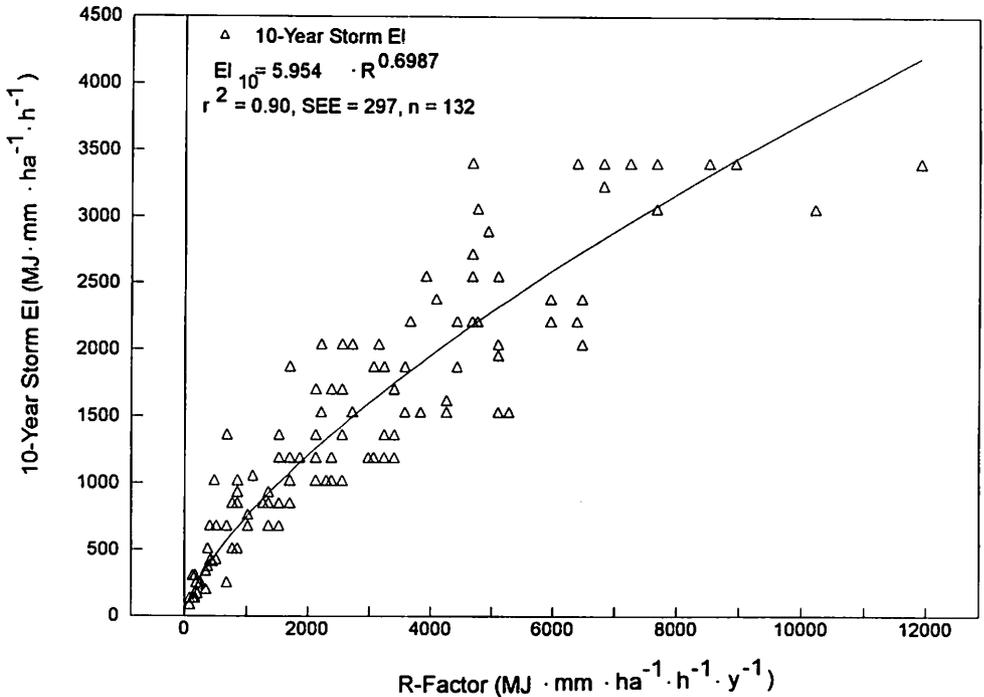


Fig. 6. Relation between 10 year storm EI and R -factor.

from R -factor differences, is about half of what would be expected for a linear relation in the form of Eq. (1). Although Eq. (1) suggests that a change in any of the six factors would result in an identical change in predicted soil loss, this is not the case with RUSLE. In RUSLE, changes in the R -factor result in modifications of the soil erodibility (K) and the cover-management (C) factor in addition to the direct effect on the soil loss prediction (Renard and Ferreira, 1993).

7. Estimation of 10 year storm EI -values

Attempts to estimate the 10 year frequency storm EI -value for US stations based on monthly precipitation data met with limited success. Using average annual precipitation (mm) and the modified Fournier index (mm) as predictors resulted in, respectively, 0.63 and 0.66 coefficients of determinations as well as 565 and 543 standard errors of the estimate. In contrast, the R -factor appears to be a good predictor of the EI_{10} .

With EI_{10} -values ($MJ\ mm\ ha^{-1}\ h^{-1}$) as the dependent variable and identified R -factor values ($MJ\ mm\ ha^{-1}\ h^{-1}\ year^{-1}$) as the independent variable, the equation ($n = 132$)

$$EI_{10} = 5.954(R\text{-factor})^{0.6987} \quad (15)$$

yielded a 0.90 coefficient of determination and 297 MJ mm ha⁻¹ h⁻¹ as a standard error of the estimate (Fig. 6).

8. Conclusions

Preferably, *R*- and the 10 year frequency storm *EI*-values would be determined as calculated by Wischmeier for all locations where RUSLE is used. Unfortunately, since the required data and/or resources necessary for this task are not available for all application sites, site-specific estimation relations or estimation relations established for similar climatic zones may have to be used to obtain the required values. While the estimated values could be considerably in error, and the predicted soil loss may be far from exact, they may be the best available for at least assessing the erosion potential or relative erosion rates from different conditions (such as management or crop) or soils.

In an effort to increase the availability of estimation relations for different climatic zones, associations based on the extensive US database have been presented.

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