The Spatial Distribution in Southern Africa of Rainfall Erosivity for Use in the Universal Soil Loss Equation

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Abstract

Rainfall erosivity parameters are essential in soil loss modelling. Parameters reflecting the effects of soil, vegetation and topography can be estimated from tables and nomographs which are currently available. Rainfall erosivity, however, is a climatic factor which can only be determined from local rainfall data. The derivation of the rainfall erosivity factor EI_{30} from four parameters based on daily rainfall values is discussed and design values of the term currently used in the Universal Soil Loss Equation are presented in the form of an iso-erodent map for Southern Africa. Annual values of rainfall erosivity which may be expected for a 25 year return period are also given.

Introduction

Since measurement of soil loss is both a costly and time consuming process, a model with which it may be estimated with some confidence is a valuable planning tool. Soil loss estimation is a means by which conservation practices may be based on the quantification of the relevant soil, topography, vegetation and management factors and the relation of these factors to regional and temporal characteristics of rainfall erosivity. Parameters reflecting the effects of the first four factors can be estimated universally from tables and nomographs which are currently available (Wischmeier and Smith, 1978). It may therefore be said that estimation of soil loss depends largely on the availability of a suitable quantifiable rainfall erosivity parameter.

This parameter must describe adequately the ability of rainfall to cause erosion by detachment of soil particles. It must be able to give sufficiently accurate estimates of soil loss for conservation planning and should have general applicability so that different factors or soil loss relationships are not required in areas in which rainfall characteristics differ. Since the early stages of soil loss research, rainfall kinetic energy has attained wide recognition as a causative factor in the erosion process and the spatial distribution of mean annual rainfall energy, E, for use in the Soil Loss Estimation Model for Southern Africa (Elwell, 1977) has been presented by Schulze (1980). However, use of rainfall kinetic energy alone is not always sufficient to describe the relative rainfall erosivity of any two locations in which the intensity of rainfall may vary considerably. A rainfall erosivity term to which soil loss is similarly related in regions of different rainfall patterns is thus a prerequisite for a soil loss equation not limited to specific geographical locations.

The Universal Soil Loss Equation (USLE)

An erosivity term which is in general use in the United States of America and elsewhere is the product of the kinetic energy, E, of falling rain and its maximum 30 min intensity, I_{30}. This parameter, designated EI_{30}, appears to account for the kinetic energy of rainfall as well as for sustained periods of high intensity of rainfall. Following stringent statistical tests of results from experimental plots, EI_{30} is now widely recognised as being sufficiently accurate for soil loss modelling and is a parameter in the now generally used Universal Soil Loss Equation (USLE) which may be expressed as

$$A = RKLSCP$$

where

A = computed soil loss per unit area, expressed in the units selected for K and the period selected for R
R = rainfall and runoff factor, expressed in units of rainfall erosivity, generally the long term average annual value of EI_{30}
K = a soil erodibility factor
LS = a slope length and gradient factor
C = a cover and management factor
P = support practice factor.

Wischmeier and Smith (1978) state that the USLE may be applied wherever its factor values are known. The development of design aids in the form of graphs, nomographs and tables has made possible the calculation or estimation of the USLE factors K, LS, C and P.

The rainfall erosivity factor, R, however, is a climatic parameter which can only be determined from local data. Any application of the USLE in Southern Africa therefore depends on the availability of design values of R.

Definition and Conceptual Basis of EI_{30}

The definition of EI_{30} given above is qualitative only and quantification of the term requires conventions to be adopted with respect to units and identification of discrete rainfall events which are taken into account individually in calculating an annual value of EI_{30}. In the USA kinetic energy of rainfall is measured in ft tons per acre per in and intensity as in per h. This leads to a somewhat cumbersome definition of the units of EI_{30}.

In order to avoid confusion, values of EI_{30} obtained were divided by 100 to reduce them to manageable orders of magnitude and the units referred to simply as erosion index units (Wischmeier and Smith, 1978). In the metric system as used in Southern Africa rainfall kinetic energy is expressed in $J\ m^{-2}$ over a unit of time and intensity in $mm\ h^{-1}$. For the purposes of computation of EI_{30} in Southern Africa "units of erosivity" are taken as the units obtained when the product of energy and intensity in metric units is divided by 1 000.

In calculating EI_{30} a rainfall event is taken as a period during which more than 12,5 mm rain falls, separated from any other periods of rain by more than six hours. Showers of less than 12,5 mm are included only if 6,3 mm or more falls in 15 min. E is the total kinetic energy for the event and I_{30} is the maximum 30 min intensity. The effect of applying the 12,5 mm threshold rather than using all events is generally relatively small (Wischmeier and Smith, 1978). An additional convention in the calculation of EI_{30} is the application of an upper limit of rainfall intensity of 76 $mm\ h^{-1}$. This limit is imposed by Wischmeier and Smith (1978) because Carter *et al* (1974) had shown that median drop size does not increase with intensity for intensities greater than about 76 $mm\ h^{-1}$. Since rainfall kinetic energy increases with intensity because of the increase in median drop size, E will remain reasonably constant at intensities of more than 76 mm h^{-1}.

It must be stressed that EI_{30} is an empirical parameter. Its use can therefore not be justified by any conceptual reasoning but only by results from runoff plot studies in which EI_{30} yielded the best results of several energy-based parameters when regressed against the soil loss measured.

Design Values of EI_{30}

Generally the long term average annual value of EI_{30} is used in the USLE to estimate long term average annual soil loss, the purpose for which the USLE was originally proposed. The USLE was never intended to estimate soil loss for individual storms or even specific years (Wischmeier, 1976). The primary objective of this paper is therefore to present long term average annual values of EI_{30} for Southern Africa. However, Roose (1976) notes that in Mediterranian and coastal regions of North Africa it is the exceptional 50 to 100 year frequency rainfall that changes the landscape radically, while in dry or humid tropical environments the rate of soil loss depends on the sum of the ten or twenty most severe storms of the year. In Southern Africa application of the 12,5 mm threshold results in calculated annual values of EI_{30} seldom representing more than 20 storms.

It would therefore appear that long term average annual values of EI_{30} will differentiate adequately between zones of high and low erosivity. However, since the computation of annual values of EI_{30} which may be expected for various return periods is a simple undertaking once several years of EI_{30} data are available, extreme values of annual EI_{30} are also presented in this paper.

Estimation of EI_{30}

Computation of EI_{30} depends on the availability of autographic rain-gauge data. Since there is at the present time a limit to the number of Southern African stations for which EI_{30} can be computed, stations which are representative of homogeneous rainfall regions were selected as key stations. The selection of these key stations was such that sufficient data were available to allow regression of EI_{30} against suitable rainfall parameters, based on readily available daily values, for each key station. The South African Weather Bureau (1972) has divided the country into homogeneous rainfall regions on the basis of the annual march of rainfall. These regions and the selected key stations, together with 403 daily rainfall stations, are shown in Figure 1. Four parameters to which EI_{30} could be related, were considered. The four parameters selected are defined below in order of increasing complexity.

(a) Total rainfall: Total rainfall amount for a given period is the simplest rainfall parameter to which EI_{30} could be related.

(b) Effective rainfall: It was hypothesized that better correlation with EI_{30} may be expected if total rainfall were replaced by "effective rainfall", i.e. rainfall excluding all individual events assumed non-erosive, by definition those less than 12,5 mm separated by more than 6 hours.

(c) Modified Fournier's Index: A modification of Fournier's Index was used, in which

$$\sum_{i=1}^{12} \frac{Pe_i^2}{P} = \text{an index of rainfall erosivity}$$

where

Pe_i = effective rainfall amount for month i in mm, and
P = annual rainfall, in mm.

(d) Burst Factor: Since the EI_{30} term includes rainfall intensity as well as kinetic energy, it was assumed that some function of rainfall which includes an intensity characteristic would correlate well with EI_{30}. Maximum rainfall amount for the observational day in a given time period is readily obtainable and gives some indication of intensity. The so-called Burst Factor as suggested by Schulze (1979) was given by Smithen (1981) as

$$\sum_{i=1}^{12} \frac{M_i\, Pe_i}{P} = \text{an index of rainfall erosivity}$$

where

M_i = maximum daily rainfall for month i in mm,
Pe_i = effective rainfall in mm for month i and
P = annual rainfall in mm.

Method and Results

Following tests on the effects of transforming data and using it at the monthly and annual levels, simple linear regression on untransformed data was used to relate annual values of EI_{30} from the key stations to each of the four rainfall parameters selected. The best-fit parameters selected for the respective key stations to estimate EI_{30} are given in Table 1.

TABLE 1
FINAL SELECTION OF RAINFALL PARAMETERS USED AND CORRELATION COEFFICIENTS OBTAINED AT 13 KEY STATIONS FOR ESTIMATION OF EI$_{30}$

Station	Selected Rainfall Parameter	No. of Years' Data	r*
Bloemfontein (JBM Hertzog Airport)	Effective Rainfall	17	0,92
Kimberley	Effective Rainfall	20	0,77
Grootfontein	Effective Rainfall	15	0,93
Upington	Effective Rainfall	19	0,86
Cathedral Peak	Effective Rainfall	12	0,90
Cape Town (DF Malan Airport)	Fournier's Index	20	0,93
Port Elizabeth	Fournier's Index	19	0,97
Pretoria	Burst Factor	19	0,72
Johannesburg (Jan Smuts Airport)	Burst Factor	23	0,92
Pietersburg	Burst Factor	19	0,82
Cedara	Burst Factor	10	0,97
Durban (Louis Botha Airport)	Burst Factor	19	0,74
East London	Burst Factor	19	0,97

*All values of r significant at the 1% level

On the assumption that the EI$_{30}$: rainfall relationships established at the key stations were representative of other stations (with just daily rainfall data) within the respective homogeneous rainfall regions, the equations developed (Smithen, 1981) were used to estimate EI$_{30}$ at the 403 stations shown in Figure 1. This extrapolation provided not only long term average annual values of EI$_{30}$ but also a data file from which the probability of occurrence of annual EI$_{30}$ values could be estimated.

Design Values of EI$_{30}$ in Southern Africa

Estimated long term average annual EI$_{30}$ values were plotted on a map of Southern Africa and lines of equal rainfall erosivity, expressed in EI$_{30}$ units, could be drawn. These lines, known as iso-erodent lines, form a basis from which EI$_{30}$ can be estimated for any location in Southern Africa. The iso-erodent map, shown in Figure 2, therefore provides a means of obtaining the R factor of the USLE.

The pattern reflected by the iso-erodent lines is similar to that reflected in the map of mean annual rainfall kinetic energy, E, drawn by Schulze (1980). There are important differences in the relative magnitudes of EI$_{30}$ and E, however. Both maps indicate low rainfall erosivity in the South Western Cape and high erosivity in the Eastern Cape, Natal and the Eastern Transvaal. The highest values of E shown in the Eastern Transvaal are eight times the lowest values shown in the South Western Cape, while the corresponding ratio for EI$_{30}$ is ten. For the South Western Cape and the Eastern Cape these ratios are five and eight and for the South Western Cape and Natal they are six and ten for E and EI$_{30}$ respectively. Furthermore, the highest E values for Natal occur in the Drakensberg on the Lesotho border while values of EI$_{30}$ occur in the Natal Midlands which are higher than those in the Drakensberg. If the relative magnitude of rainfall erosivity is to be used to assess the relative erosion hazard at a location, however, the direct proportionality of soil loss to EI$_{30}$ in the USLE must be borne in mind.

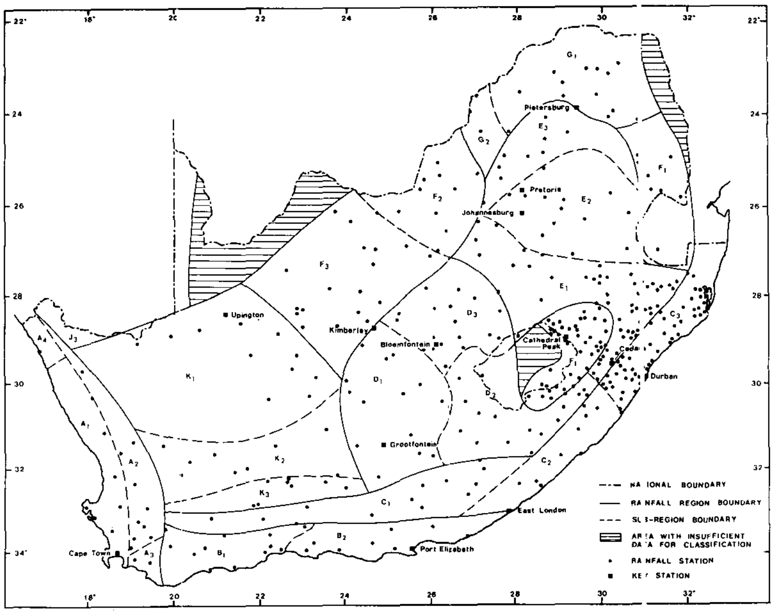

Figure 1
Rainfall regions and stations

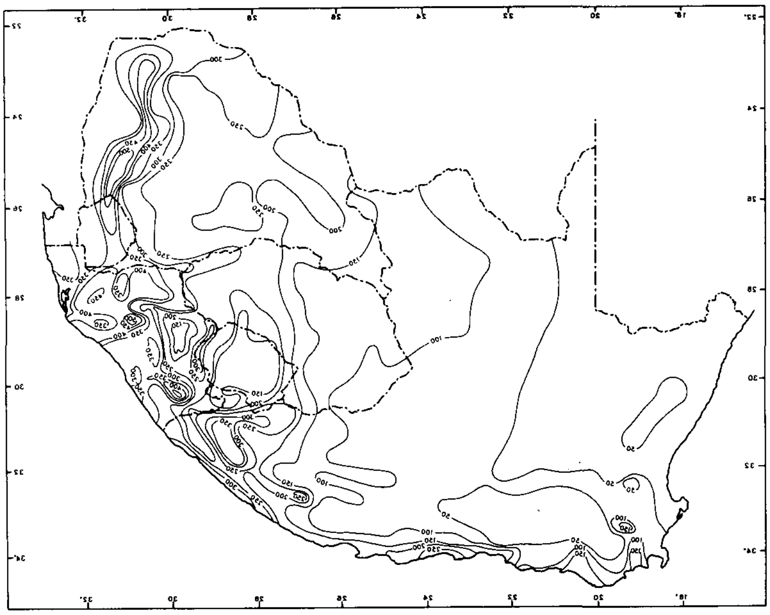

Figure 2
Estimated average annual EI_{30}

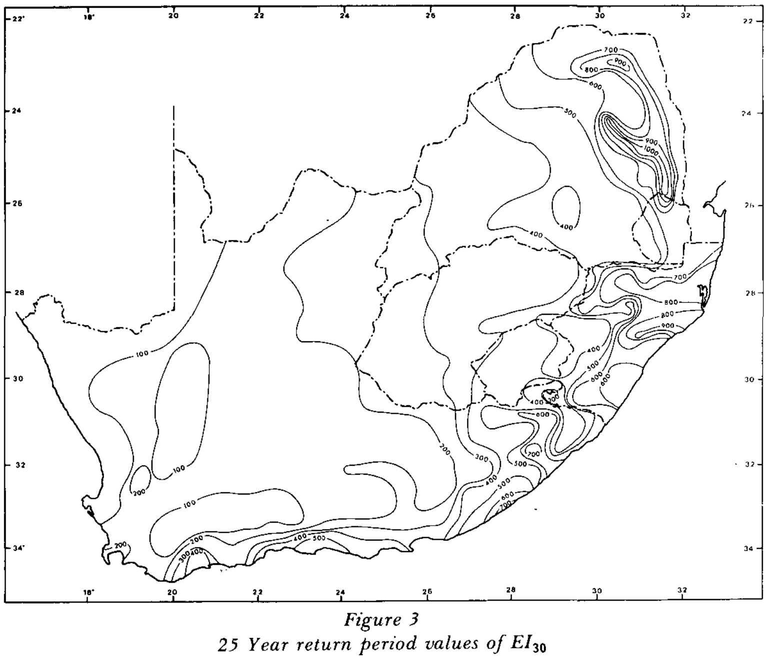

Figure 3
25 Year return period values of EI_{30}

The exceptional rainfall event or wet year can frequently change the landscape radically in terms of soil loss, for example, the Laingsburg floods of 1981 and their resultant soil losses showed this as did Roose's (1976) findings in North Africa. The data file generated by the estimation of annual EI_{30} for the 403 stations each with an average of 55 years of record, makes possible the estimation of design values of annual EI_{30}. The Extreme Value Type I (Gumbel) distribution was used to estimate annual values of EI_{30} for a 25 year return period. Figure 3 shows the spatial distribution of the 25 year return period value of EI_{30}.

Conclusion

The paucity of suitable long term data for the rigorous computation of EI_{30} necessitates the development of estimation procedures for the extrapolation of the term. Using parameters which were more complex than total rainfall amount, but which were nevertheless readily obtainable from daily rainfall data and which could be related to EI_{30}, estimation of the term was possible at key stations with rainfall intensity data. By extrapolation long term average annual and extreme annual values of EI_{30} were obtained and their distributions shown.

The availability of these values of EI_{30} for Southern Africa makes possible the application of the USLE, at least on a tentative basis.

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