The Distribution of Kinetic Energy of Rainfall in South Africa — A First Assessment

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Abstract

With considerable research effort being expended on soil loss modelling in Southern Africa at the present time, the need has arisen for information on the distribution of the rainfall energy input into these models. This paper describes the derivation of rainfall kinetic energies, E, from records of rainfall intensity at 14 stations located in a variety of rainfall regions in South Africa. Generalized energy : rainfall relationships are established at the monthly level of data using the Soil Loss Estimation Model for Southern Africa (SLEMSA) equation for E and from these mean annual, summer and winter distributions of E are mapped for the Republic.

Kinetic Energy and Rainfall Intensity

The study of soil erosion has, over the past two decades, become more and more hydrologically oriented as insight into processes and mechanisms of erosion has been gained, for it is rainfall that detaches soil particles and runoff that provides the transporting mechanism for the eroded material. According to Meyer (1965) the characteristics of rainfall that need to be known because of their influence on soil erosivity include

- rainfall intensity,
- the raindrop size distribution,
- raindrop fall velocity, and
- the angle of raindrop impact on the ground.

While the last-mentioned factor is well-nigh impossible to estimate for individual storms, the first three factors, in combination, find expression in the kinetic energy, E, of rainfall. It is the E of falling raindrops that possesses ability to break down the structure of the soil, splash particles into the air and thereby initiate soil erosion.

Because information on rainfall intensity is relatively easily obtainable (from rainfall recorder charts) but that on the other factors is not, researchers have sought relationships between E and rainfall intensity, I. Utilizing the classic findings of Laws (1941) on terminal velocities of raindrops of different diameters, and subsequent raindrop size : rainfall intensity relationships (for example, Hudson, 1963), a number of empirical E:I equations have been developed. The best known of these is probably by Wischmeier and Smith (1958), used in the Universal Soil Loss Equation (USLE), but others have been summarized by Hudson (1971) while a more recent contribution has come from Carter *et al.*, (1974).

In Southern Africa, E : I research has been undertaken in Rhodesia and an equation applied by Elwell and Stocking (1973) in their assessment of rainfall parameters and soil loss estimation, and used in SLEMSA, i.e. the Soil Loss Estimation Model for Southern Africa (Department of Agricultural Technical Services, 1976), gives

$$E = 29{,}82 - 127{,}51/I \ (\mathrm{J\ m^{-2}\ mm^{-1}\ rainfall}).$$

With considerable research effort being expended on soil loss modelling in Southern Africa at the present time, the need has arisen for information on the distribution of the rainfall energy input into these models. This paper describes the derivation of rainfall kinetic energies from records of rainfall intensity at 14 stations located in a variety of rainfall regions in South Africa. Generalized energy : rainfall relationships are established at the monthly level of data using the SLEMSA equation for E and from these mean annual, summer and winter distributions of E are mapped for the Republic.

The Data

For selected meteorological stations in South Africa the S.A. Weather Bureau tabulates for each month the number of occurrences of 15-min rainfall amounts for the following class intervals of rainfall:

0,1 – 1,0 mm; 1,1 – 2,0 mm; 2,1 – 4,0 mm

and then progressing at 2,0 mm intervals to 44,0 mm in 15 min. These data are extracted manually from the autographic rain gauge charts. From these rainfall amounts mean rainfall intensities may be calculated and by using the data on the number of occurrences of these amounts together with the E : I equation, monthly estimates of rainfall energy may be made. Data of the type described above were obtained for 12 stations in South Africa for this analysis of rainfall energy.

Rainfall energy data can also be derived from charts of autographic rain gauges using clock-error-corrected digitized records. For each pair of digitized points from a recorder chart, energy may be estimated from the rainfall intensity (i.e. the rainfall difference/incremental time). Energy is then integrated for individual storms and summed for monthly totals. Such records were available for this research for Cathedral Peak and Cedara (Schulze and Engelbrecht, 1978).

In Table 1 information relating to the stations selected and the respective periods of record used in this analysis is given. Figure 1 shows the distribution of the 14 stations selected in relation to the rainfall regions of South Africa (SAWB, 1972) which delimit zones of similar inter-annual rainfall regimes. It may be seen in Figure 1 that a good distribution is attained with one or more stations in each of the major regions and sub-regions with

TABLE 1
INFORMATION RELATING TO RAINFALL ENERGY DATA USED

Station	Latitude (°S)	Longitude (°E)	Altitude (m)	Period of Record
Beaufort West	32°21'	22°35'	857	1951–65
Bloemfontein (J.B.M. Hertzog Airport)	29°06'	26°18'	1 351	1951–77
Cape Town (D.F. Malan Airport)	33°58'	18°36'	44	1956–77
Cathedral Peak	29°00'	29°15'	1 852	1963–74
Cedara	29°32'	30°17'	1 067	1967–71 1974–78
Durban (Louis Botha Airport)	29°58'	30°57'	8	1951–77
East London	33°02'	27°50'	125	1957–77
Grootfontein	31°29'	25°02'	1 270	1962–77
Johannesburg (Jan Smuts Airport)	26°08'	28°14'	1 692	1954–65
Kimberley	28°48'	24°46'	1 198	1951–77
Pietersburg	23°52'	29°27'	1 230	1951–77
Port Elizabeth	33°59'	25°36'	60	1951–77
Pretoria (Weather Bureau)	25°45'	28°14'	1 369	1965–77
Upington	28°24'	21°16'	836	1951–77

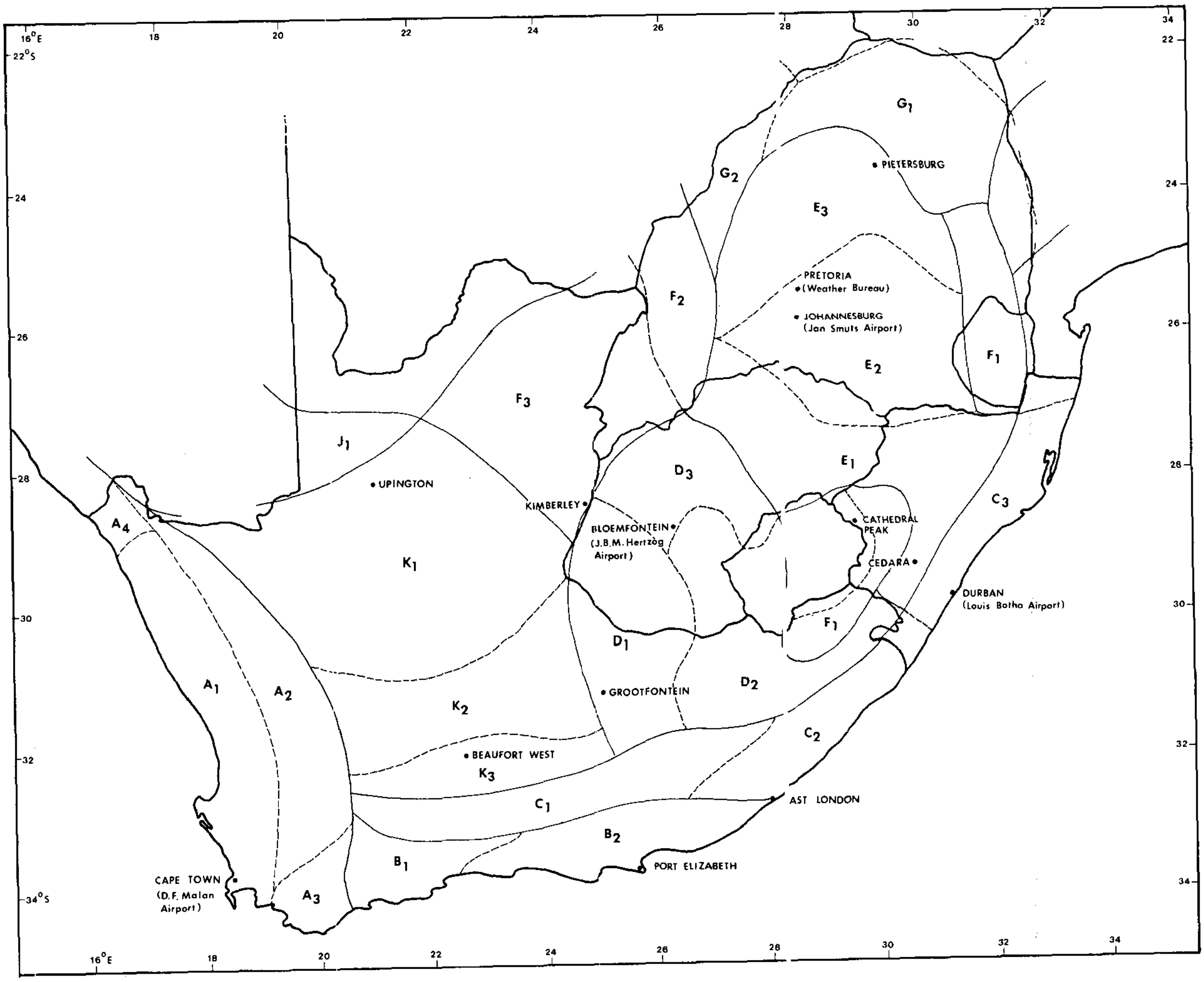


Figure 1
The distribution of stations selected for rainfall energy analyses in relation to the rainfall districts of South Africa

the exception of rainfall region G, for which information on rainfall energies could not be readily derived.

Method of Analysis

The Weather Bureau data were first punched to computer card. This was followed by an error check, whereby a computed monthly rainfall (determined by the summation of the products of occurrences and amounts for each rainfall class) was compared with the given rainfall for the month. This check revealed both punching errors and errors in the manual exraction and tabulation of the data. Obvious errors could then be corrected; where uncertainty remained as to the source or type of error, the data were rejected.

For each 15-min rainfall class, R_{15}, the kinetic energy of rainfall could then be expressed as

$$E = 29{,}82 - 127{,}51/(R_{15} * 4) * R_{15} * OCC$$

where

OCC = the number of occurrences of 15-min rainfall amounts in that class. Summation of energies for all rainfall classes yielded the total monthly estimate of rainfall kinetic energy. For the 23 rainfall classes given by the Weather Bureau the median values of each class were assumed representative of the rainfall amount. Thus an occurrence of 15-min rainfall in the 10,1 — 12,0 mm class was assigned the amount of 11,0 mm. Exceptions were, however, made in the lowest three rainfall classes, where an analysis of digitized records at Mount Edgecombe, Cedara and Estcourt showed distinct positively skewed distributions of 15-min rainfall amounts, such that most typical (modal) amounts of rainfall were found to be

0,33 mm in class 0,1 — 1,0 mm at the coast,
0,35 mm in class 0,1 — 1,0 mm in the interior,
1,35 mm in class 1,1 — 2,0 mm at the coast,
1,40 mm in class 1,1 — 2,0 mm in the interior, and
2,90 mm in class 2,1 — 4,0 mm at the coast.

Soil loss equaations such as the USLE (Wischmeier and Smith, 1965; 1978) or SLEMSA (Department of Agricultural Technical Services, 1976; Elwell, 1977) use long-term average annual or seasonal values of E as one of several inputs. Where records of E are of short duration or extend over different periods of time, as is the case with the data from the 14 stations used in the present analysis (Table 1), significant biases in the soil loss equations may therefore be introduced by the E factor. Wischmeier (1976) stresses the use of long-term averages to smooth out inter-annual E variations and suggests for the eastern United States of America, for example, the use of at least 22 years of records to overcome effects of "22 year weather cycles" there. Climatic fluctuations with different periodicities have been shown to exist in South Africa (Tyson, 1978). Furthermore, rainfall kinetic energy regimes show distinct evidence of seasonality (Schulze, 1978) depending on whether rainfall is associated primarily with local thunderstorms, with subcontinental low pressure systems or with frontal activity. To overcome the problems of periodicity and seasonality, correlations were therefore sought between E and monthly rainfall which could then be used to obtain more realistic estimates of long-term means of E. Simple linear rather than more complex regressions of E versus rainfall were found to yield best results overall.

In order to extrapolate energy estimates from the 14 selected stations to other areas in South Africa, each of the 14 stations was assigned a "domain" for which it was assumed that the respective E : rainfall equations would describe the rainfall energy regime adequately. Boundaries for the domains were delimited according to rainfall regions and sub-regions of South Africa which are defined as zones of homogeneous rainfall distributions (SAWB, 1972). The domains are shown in Fig. 2 (cf. Fig. 1). For each domain suitably distributed stations (401 in all) with long-term rainfall records were selected (SAWB, 1965). The appropriate E : R equations were then applied to the long-term records at the 401 stations to yield estimates of monthly, seasonal and annual rainfall energies.

Results

Energy: Rainfall Relationships

The monthly energy : rainfall relationships at the 14 stations are depicted graphically in Fig. 3. A number of important observations may be made from the data:

(i) Correlation coefficients between kinetic energy and rainfall were generally high for all stations and also for all months of the year. Only 5% of all the correlation coefficients were less than 0,7; 81% were above 0,8; 46% were above 0,9; and 18% of the correlation coefficients exceeded 0,95. At four stations, namely, Beaufort West, Johannesburg, Pretoria and Upington at least four months of the year displayed correlation coefficients above 0,95. Associated with the high correlation coefficients are low standard errors of mean E, indicating that predicted E values are meaningful when estimated from rainfall.

(ii) There are considerable differences in the lines of regression between months as well as between stations (Fig. 3). For the interior stations of the summer rainfall areas the high incidence of thunderstorm-derived rainfall accounts for the steep slopes in the regressions in summer months when compared with the flatter slopes for the winter months, when most precipitation is derived from low intensity frontal rainfall. The coastal stations generally display flatter E : R slopes than the inland stations as well as a less clearly defined seasonal distribution of high energy rains. Along the coast there appears a steady progression of higher rainfall kinetic energies as one moves from the winter rainfall area (Cape Town, Fig. 3) through the all-year rainfall area (Port Elziabeth) to the summer rainfall area (East London, Durban, Fig. 3). Furthermore, the coastal stations as well as Cathedral Peak in the Drakensberg (which derives a considerable proportion of its rainfall in the form of low intensity orographically-induced precipitation) are characterized by relatively large negative intercepts which again indicate a high incidence of low energy rainfall (Fig. 3). These differences are important in establishing the seasonal and annual distributions of rainfall energy in South Africa.

The Distribution of Rainfall Kinetic Energy in South Africa

By applying the above equations to long-term mean monthly rainfall data at the 401 selected stations (Fig. 2) mean monthly rainfall energy was determined (with the constraint that negative E values as computed from the equations were assigned zero

E). Annual, summer and winter distributions of E were then plotted (Figs. 4 to 6).

Annual values of rainfall energy in South Africa exceed 10 000 J m^{-2} only east of 28°E in patches along the coast and again along the Drakensberg escarpment from Transkei through Natal and the eastern to the northern Transvaal, with a wedge of high rainfall energies towards the Witwatersrand region. While this wedge may be ascribed to a predominance of high intensity rains there in summer (cf. Fig. 3), the main reason for the other regions of high E is an abundance of rainfall. Isolated patches with energies greater than 20 000 J m^{-2} occur along the Eastern Transvaal escarpment. Mean annual rainfall energy is generally below 2 500 J m^{-2} west of 23°E and north of 34°S. Unlike the eastern escarpment, the southern escarpment areas do not stand out as regions of high rainfall energy because of the lower rainfall intensities generally occurring in the winter and all-year rainfall regions.

With the high incidence of thunderstorm activity in the months October to March in the summer rainfall areas of South Africa and the predominance of winter rainfall in the south-western Cape, summer and winter energy distributions have been mapped separately. A comparison of summer and annual energy totals (cf. Figs. 5 and 4) reveals that over most of South Africa 80% to 95% of the rainfall energy occurs in summer. Not even in the winter rainfall region do the April—September rainfall energy totals attain values of great significance for erosion studies, with long-term means of only 3 000 to 5 000 J m^{-2} in the high rainfall region of the south-western Cape (Fig. 5).

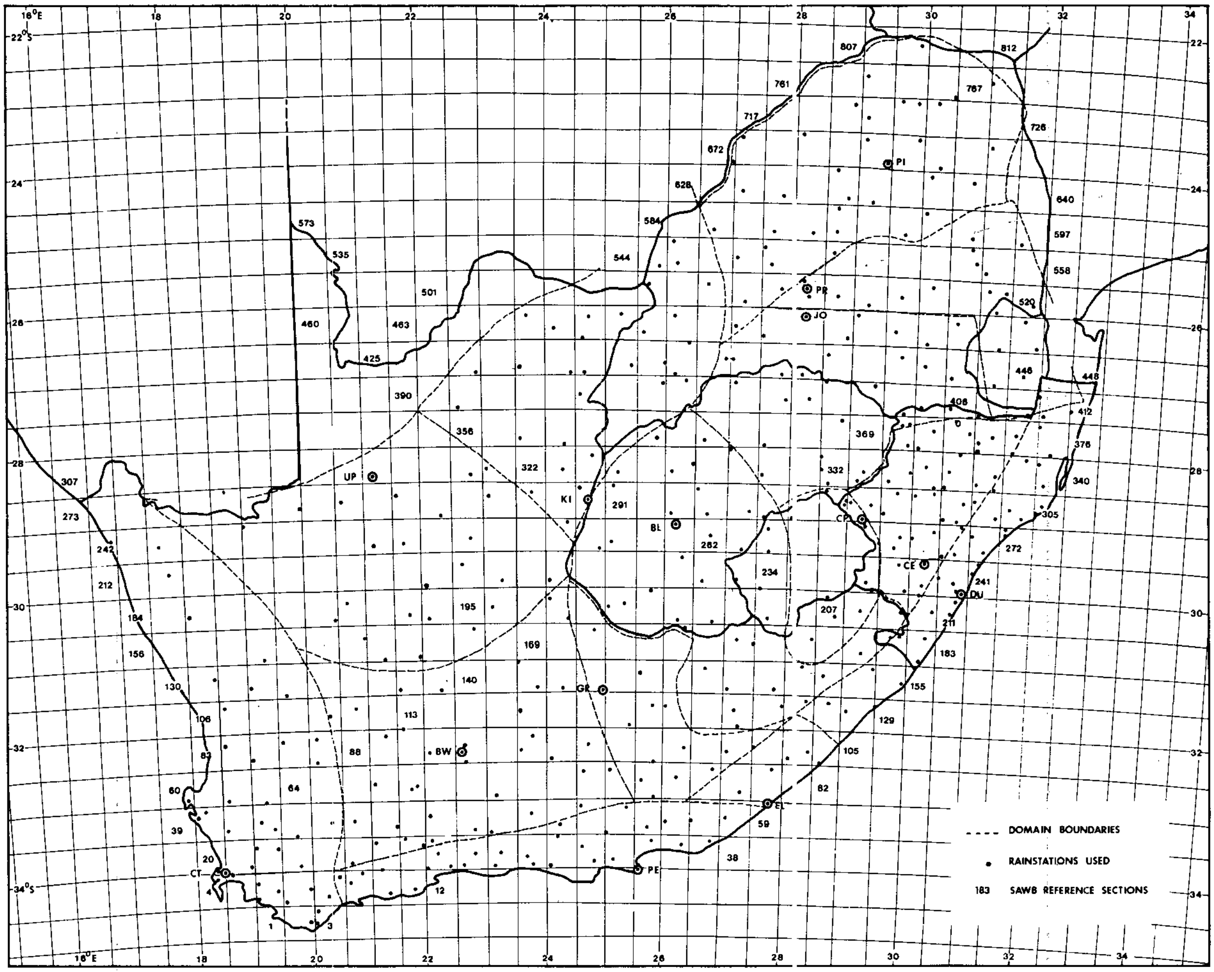


Figure 2
Rainfall energy domains and the distribution of stations to which E : R equations were applied

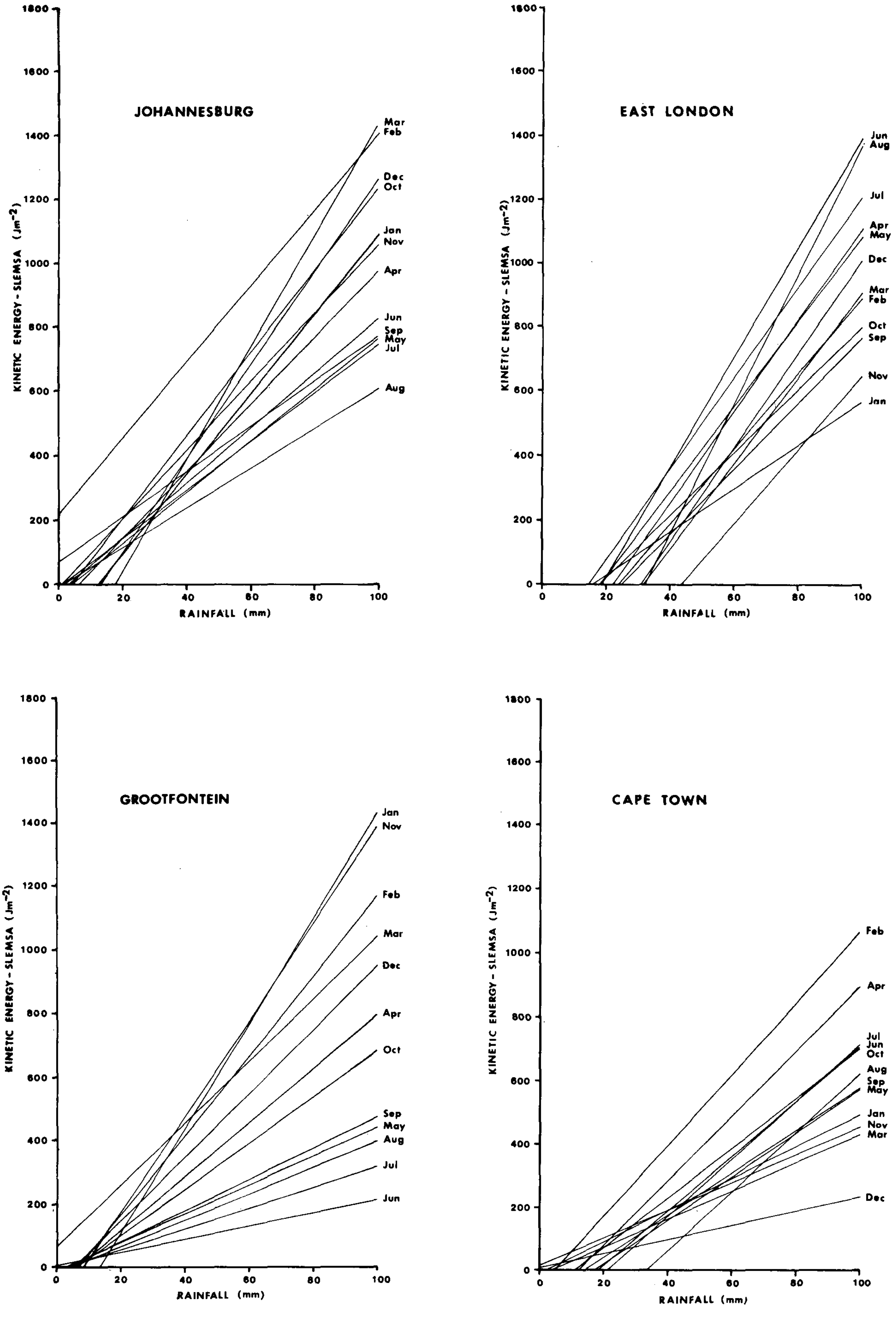


Figure 3
Monthly energy : rainfall relationship at 14 stations

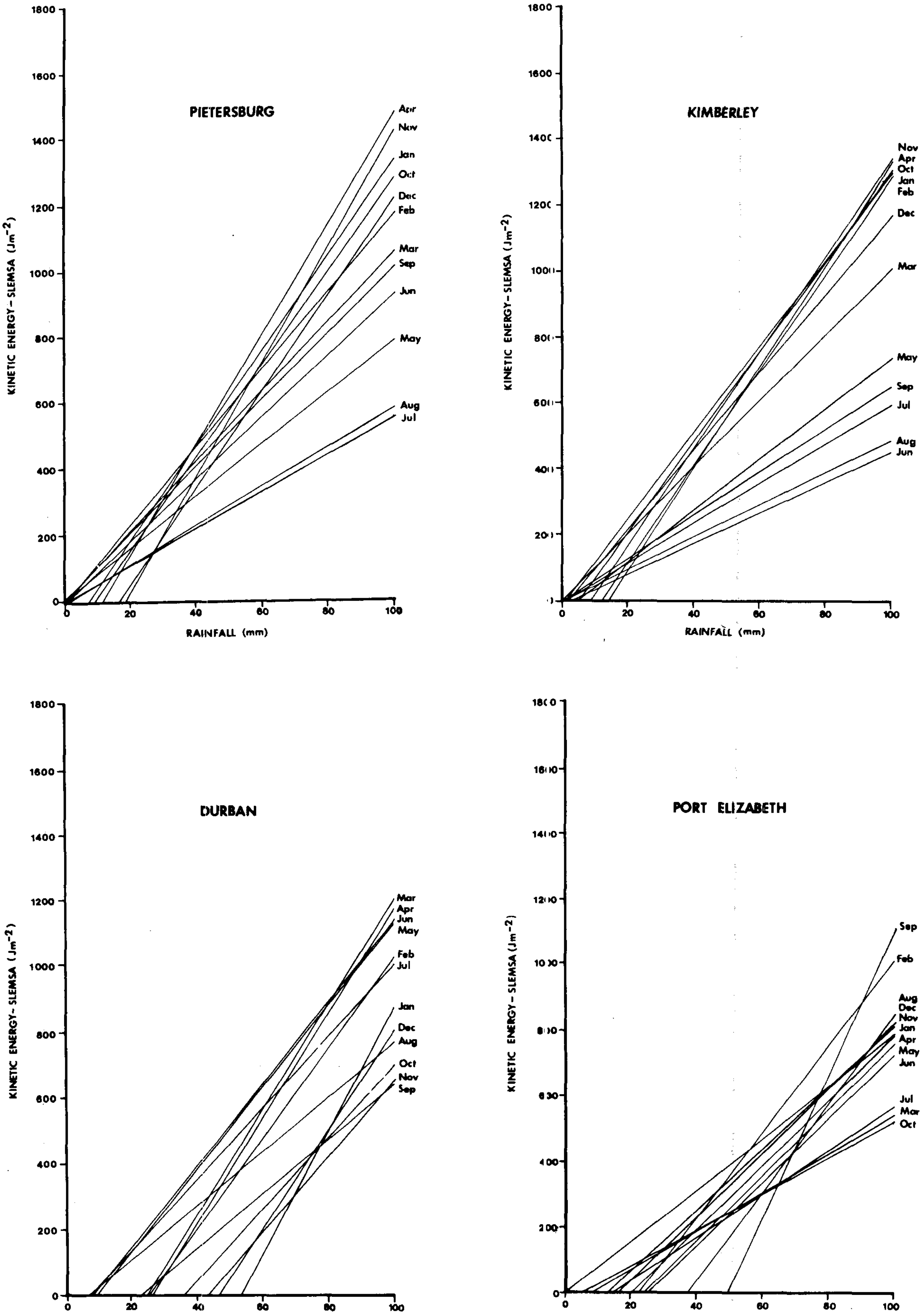


Figure 3 (continued)
Monthly energy : rainfall relationship at 14 stations

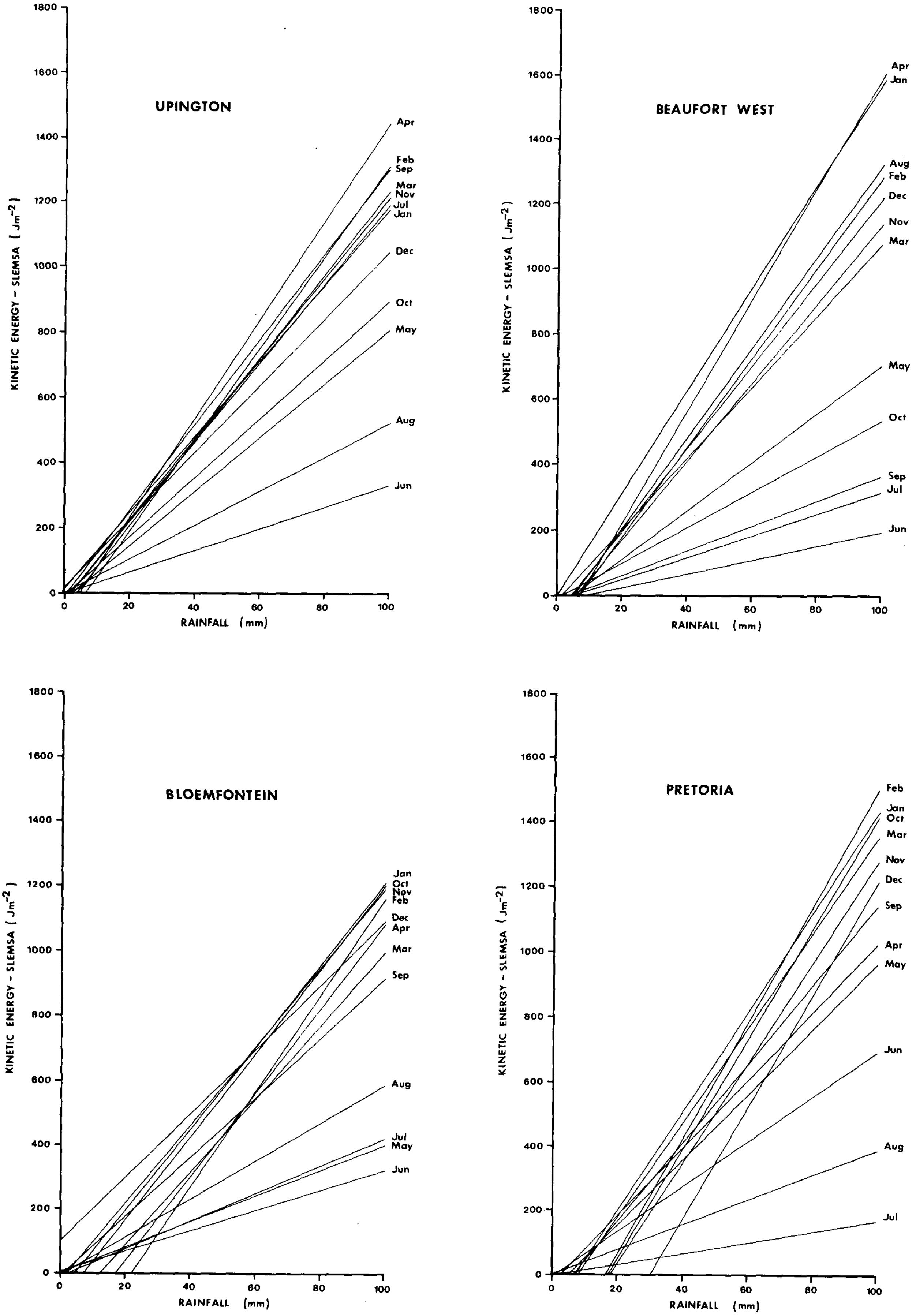
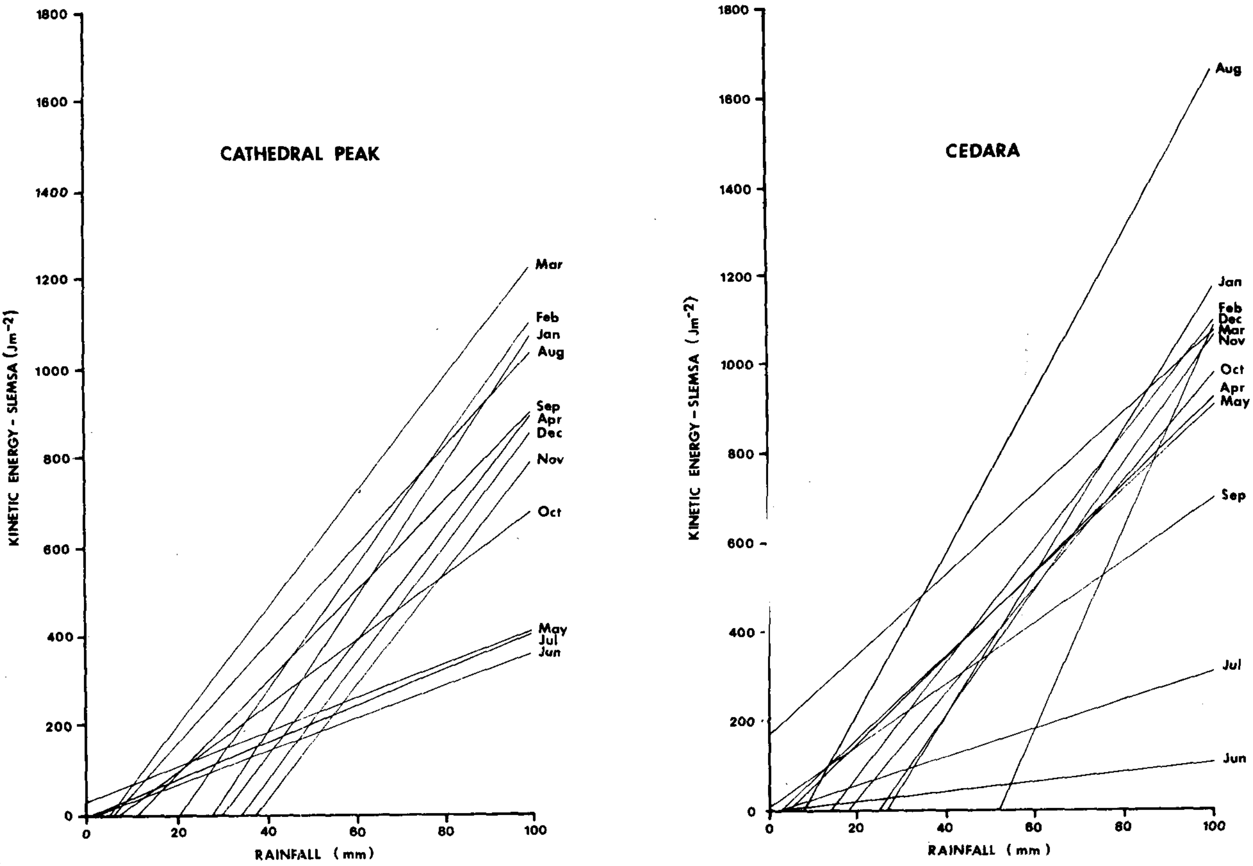


Figure 3 (continued)
Monthly energy : rainfall relationships at 14 stations



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Monthly energy : rainfall relationships at 14 stations

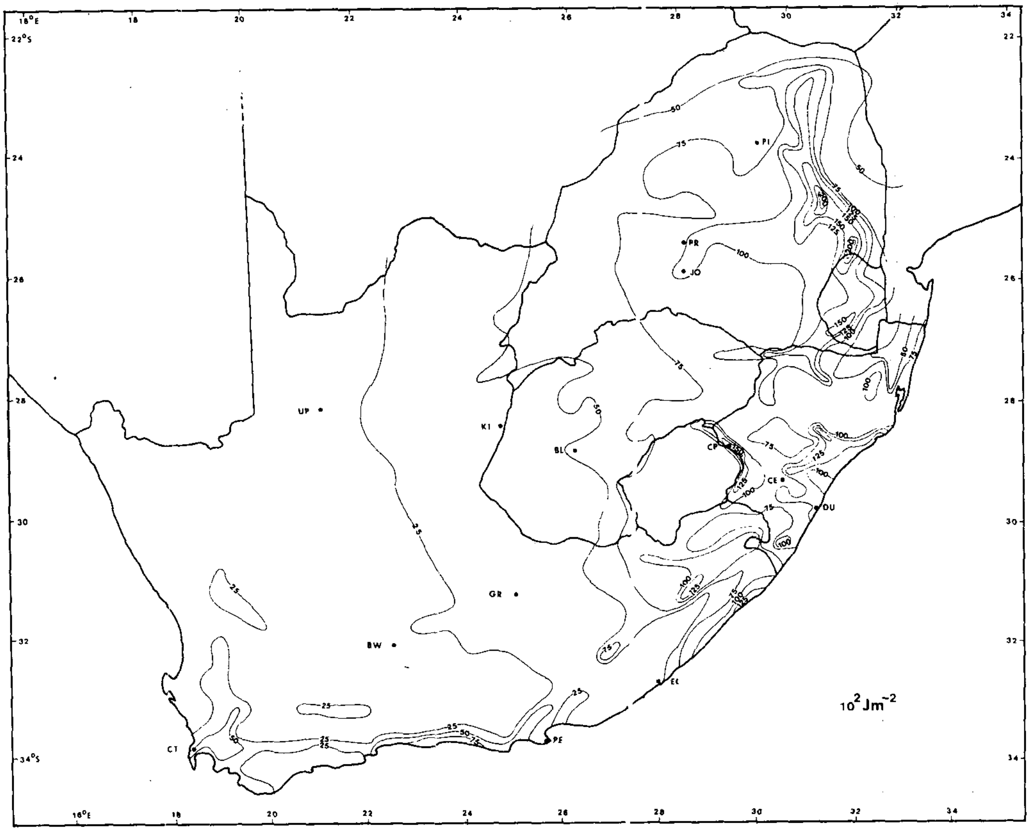

Figure 4
The distribution of mean annual E in South Africa

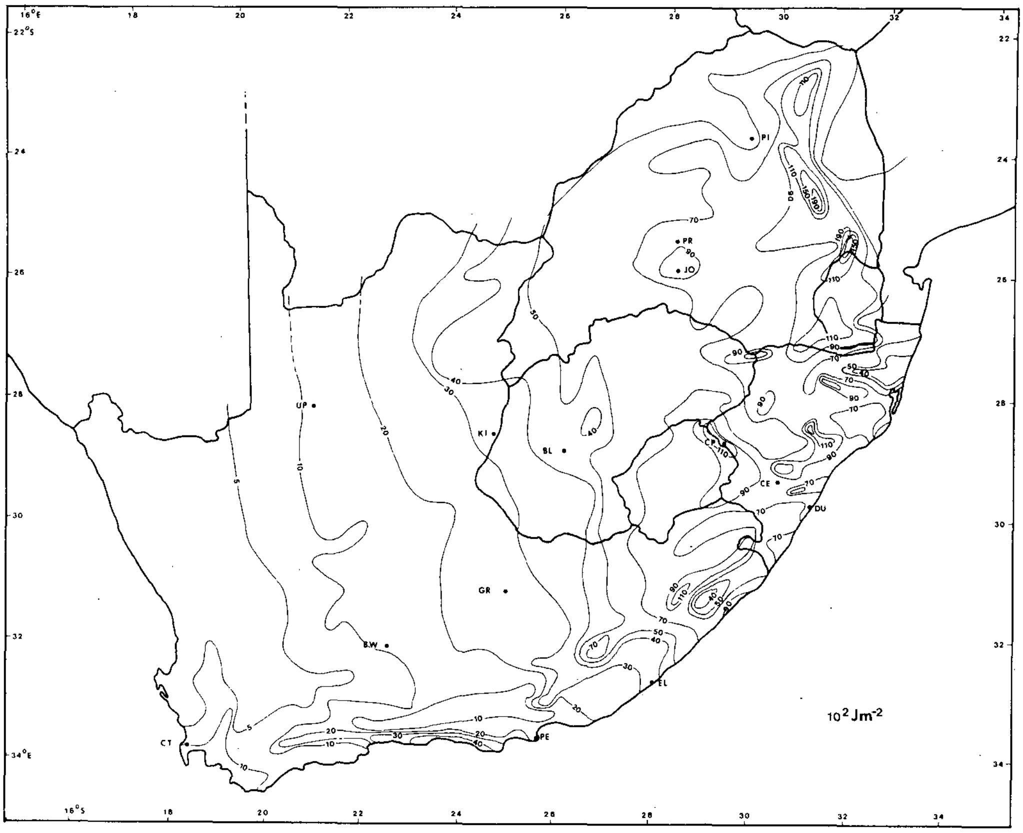

Figure 5
The distribution of mean summer (October to March) E in South Africa

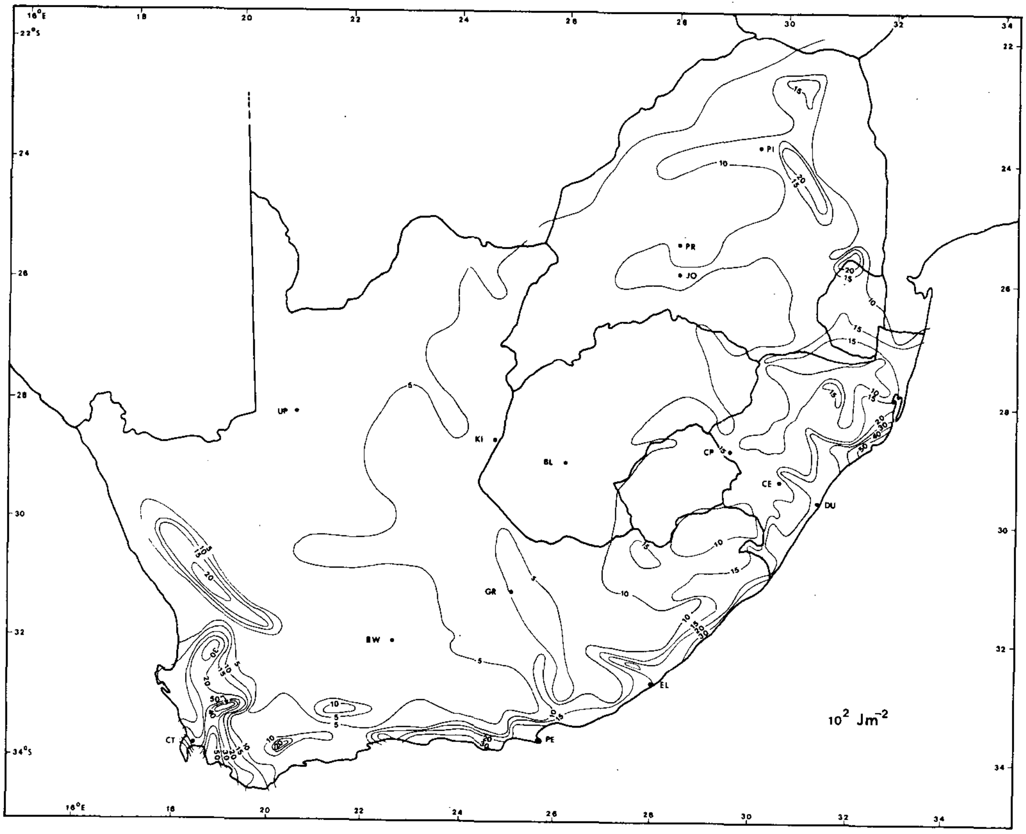

Figure 6
The distribution of mean winter (April to September) E in South Africa

Conclusions

With the paucity of soil loss measurements in South Africa research emphasis is at present focussing on the application and adaptation of physically based soil loss models such as the USLE and SLEMSA. SLEMSA, in a recent regional application to the Drakensberg (Schulze, 1979) has been shown to be very sensitive to the rainfall energy input. With little knowledge on the magnitudes and on the patterns of rainfall energy in South Africa, a first attempt has therefore been made to derive regional rainfall energy equations and to map distributions of E.

Although results appear encouraging it must be stressed that the findings of this paper are but a first and unsophisticated assessment of E. Much research in this vital field of applied hydrology is required in South Africa – more base stations are needed, as are longer records, a digitized rather than manually extracted data base and information on highest 30-min rainfall intensities of storms for the USLE's erosivity factor. Regressions of energy against indices other than monthly rainfall amounts may furthermore improve estimations at stations without autographic raingauges and research in this direction is already under way.

Acknowledgements

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