Rainfall Intensities, Kinetic Energies and Probabilities: Examples of Applied Climatological Studies of Natal*

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Abstract

First results of applied climatological research into maximum expected rainfall intensities for selected short period durations, frequencies of occurrences of high intensity rainfalls and regional/seasonal variations as well as frequency distributions of the kinetic energy of rainfall are given for selected stations in Natal. These results are derived from digitized rainfall recorder charts. Furthermore, preliminary findings, based on analyses of daily rainfall records of Natal stations, on the magnitudes and distributions of potential flood producing rains of longer durations and on various climatological drought indices, are also discussed and illustrated.

Introduction

In 1974 a project into small catchments hydrology, funded by the Water Research Commission, commenced in the Department of Agricultural Engineering at the University of Natal, Pietermaritzburg, in its Agricultural Catchments Research Unit.

Research in the Unit concentrates primarily on extreme hydrological events, and particularly on floods. A considerable amount of applied rainfall climatology is therefore made use of and is being undertaken.

Two main lines of applied rainfall research are being followed at present. First extreme rainfall intensities and the kinetic energy associated with rainfall are being examined, using output from digitized rainfall recorder charts, and secondly, probability, extreme value and frequency analyses of more readily accessible daily rainfall records are being undertaken, yielding insight into, e.g. the distribution and characteristics of potential flood producing rains or of various indices of drought. At the present the research is confined to Natal and to East Griqualand regions.

This paper on applied climatology reviews some findings of but one of the facets of hydrological research being carried out in the Unit. The emphasis here is on approaches and preliminary results rather than on methods or on literature surveys. Detailed results of the individual research projects funded by the Water Research Commission in this hydrological investigation are published separately on completion of the projects.

Analyses from Digitized Rainfall Recorder Charts

Background

Many engineering design problems centre around the expected magnitude of a storm event of a given duration for a given return period. Such problems face the civil engineer in the design of city stormwater systems, culverts or bridges, as well as the agricultural engineer designing a small dam, a waterway or a contouring system. Since most such structures are constructed in small catchments with only first and second order stream segments, and therefore with times of concentration of the catchments ranging from a few minutes to one hour, particular attention has to be paid to analyses of short duration, high intensity storms.

Rainfall recorder charts from ongoing and former small catchments investigations in Natal under the auspices of the Water Research Commission (Cedara and Mtunzini), the Departments of Forestry (Cathedral Peak) and of Agricultural Technical Services (Ntabamhlope/Estcourt) as well as from agencies like the S.A. Weather Bureau and the S.A. Sugar Association Experiment Station are being digitized.

In order to maximise all possible use of the information from the charts, especially for short duration events, *breakpoint* digitizing to a resolution of 2 min is undertaken rather

than fixed *time point* digitizing with a resolution of (say) 15 min. In break-point digitizing a time vs. height value is digitized at every change in the slope of the rainfall trace irrespective of whether this change occurs at close time intervals or not. Significantly higher extreme intensity values than those published by the Weather Bureau (1974) are being attained by this procedure for storm events of less than two hours' duration.

Maximum Expected Intensities for Selected Return Periods

Maximum annual rainfall intensities for given durations were plotted on Gumbel extreme probability paper using 12 years of digitized records from Cathedral Peak (1963—74) on the foothills of the Drakensberg, 10 years from Ntabamhlope (1964—73) near Estcourt and 9 years from Cedara (1967—71; 1974—77) in the Natal Mistbelt. Some results are given in Fig. 1, which illustrates that there appear marked regional variations of expected maximum intensities. For 5 min events it may be seen that Cedara and Ntabamhlope yield far higher values than Cathedral Peak while for events of say 15 min, Ntabamhlope attains the highest magnitudes. For longer duration events Fig. 1 shows further changes in the patterns, with expected maximum intensities at Cedara and Cathedral Peak increasing relative to those at Ntabamhlope for 720 min events.

Knowledge of such differences in probable extreme intensities is vital to the design of structures on catchments of varying size and times of concentration in different parts of the country and results from hitherto undigitized stations are slowly adding more realistic values to those considerable areas of Natal where only crude estimations have been made in the past because so few stations had been analysed. In interpreting the results, however, it should be borne in mind that there are sampling errors inherent in the analysis of short records of the order of 10 years.

Frequency of Occurrence of High Intensity Rainfalls

While one is tempted to analyse and interpret only extreme intensities for design purposes, it is as important from the water resources, flood control or soil conservation viewpoint to ascertain the frequency of occurrence of high intensity rainfalls. It is the *frequency* of high intensity rains that largely influences volumes of sediment lost from or nutrients flushed out of a catchment.

The frequencies of occurrence of rainfall events above threshold intensities for selected durations were therefore examined for the same three stations, viz. Cathedral Peak, Ntabamhlope and Cedara using the currently available data. Figure 2 illustrates that, while Cedara has most occurrences of 5 min rainfall events with intensities exceeding 50 mm h^{-1} and while very similar frequency distributions exist for 15 min events above the 30 mm h^{-1} intensity threshold, it is at Cathedral Peak that markedly higher frequencies of relatively high intensity rains for durations exceeding one hour occur, particularly in the summer/autumn months December — April. The probable cause of this is the orographic effect on rainfall induced by the Drakensberg mountain range there. Again it must be stressed, however, that only relatively short records were used in the above analysis.

The Kinetic Energy of Rainfall

The KE of falling raindrops, given by KE = ½ mv^2, is an im-

portant measure of its ability to break down the structure of the soil surface, splash particles into the air and to initiate soil erosion. Utilizing the classic findings of Laws (1941) on terminal velocities of raindrops of different diameters, and subsequent raindrop size : rainfall intensity relationships (e.g. Hudson, 1963), a number of empirical equations relating to KE to intensity have been developed, the best known of which is probably that by Wischmeier and Smith (1958).

In this paper, however, the equation applied in Rhodesia by Elwell and Stocking (1973) is being used, in which

$$KE = (29{,}82 \ - \ \frac{127{,}51}{I} \ ) \ J \ m^{-2} \ mm^{-1} \ \text{rainfall and where the}$$

intensity, I, is in mm h^{-1}. For each pair of digitized points from a recorder chart, therefore, the KE is being estimated from the rainfall intensity, integrated for individual storm events and summed for days, months or years. (It may be deduced from the above equation that a threshold intensity of 4,28 mm h^{-1} is assumed for rainfall energy *per se* to have any erosive effects).

Regional and Seasonal Variations of KE

Rainfall: KE relationships have thus far been established for the three Natal stations already named, viz. Cathedral Peak, Ntabamhlope and Cedara. In Figure 3 it may be seen that considerable differences in annual values of KE exist, especially between Ntabamhlope and Cathedral Peak, where for a given annual rainfall of (say) 750 mm at both stations, KE differences of around 40% exist.

At the individual stations even more marked differences in the rainfall:KE relationships appear for the various rainfall intensity 'seasons' within the year. The 'frontal rainfall season' in the winter months, displays much lower KEs per unit of rainfall (in particular at Cathedral Peak) than the 'thunderstorm season' of mid-summer. (It is of interest to note, also, that the grouping of months with similar rainfall:KE equations is different for each of the three stations). In the relationships illustrated in Figure 3 the correlation coefficients were generally high (r > 0,85) and all the tests were significant at the 0,05 level.

## The Frequency Distribution of KE per Unit of Rainfall

Regional and seasonal differences of KE having been established for the three selected stations, an analysis was carried out on all storms yielding 20 to 30 mm rainfall per day (this amount being considered typical of good thundershower as well as of frontal rains), in order to establish whether differences between stations existed in the distribution of KE per unit of rainfall.

Again marked differences were exhibited (Figure 4), with Ntabamhlope, for example, being characterized by high frequencies of high intensity storms, while the modal value of Cedara was found in a lower KE class and that of Cathedral Peak in an even lower KE class. Furthermore, Cedara, being located on an escarpment in the socalled Natal Mistbelt, displays a high frequency of low KE per mm rainfall values and Cathedral Peak has an almost platikurtic distribution of KEs per unit of rainfall.
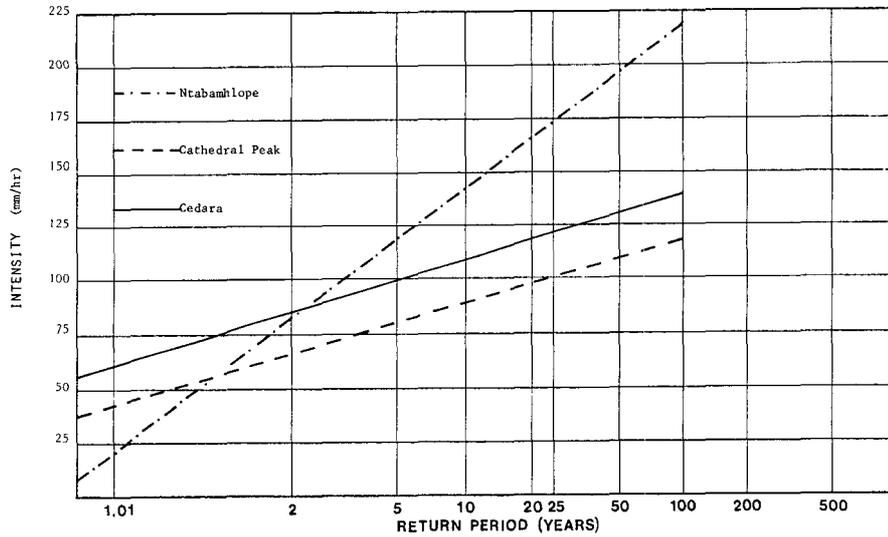
The Use of KE Studies

From the above discussion it may be deduced that important

5 MINUTE EXTREME RAINFALL
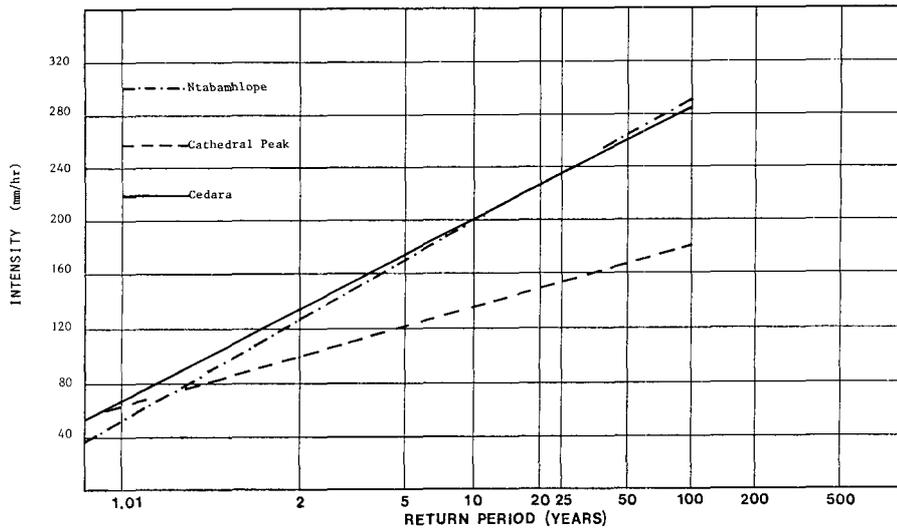
15 MINUTE EXTREME RAINFALL
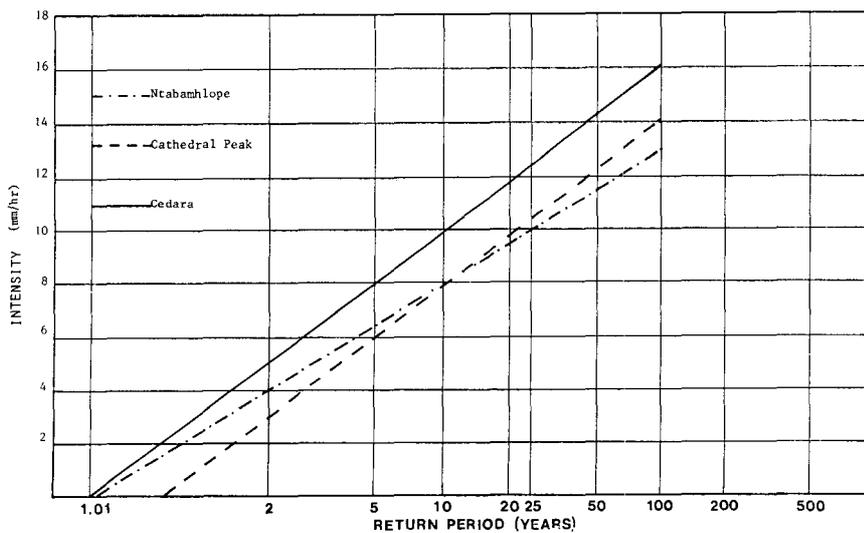

720 MINUTE EXTREME RAINFALL

Figure 1
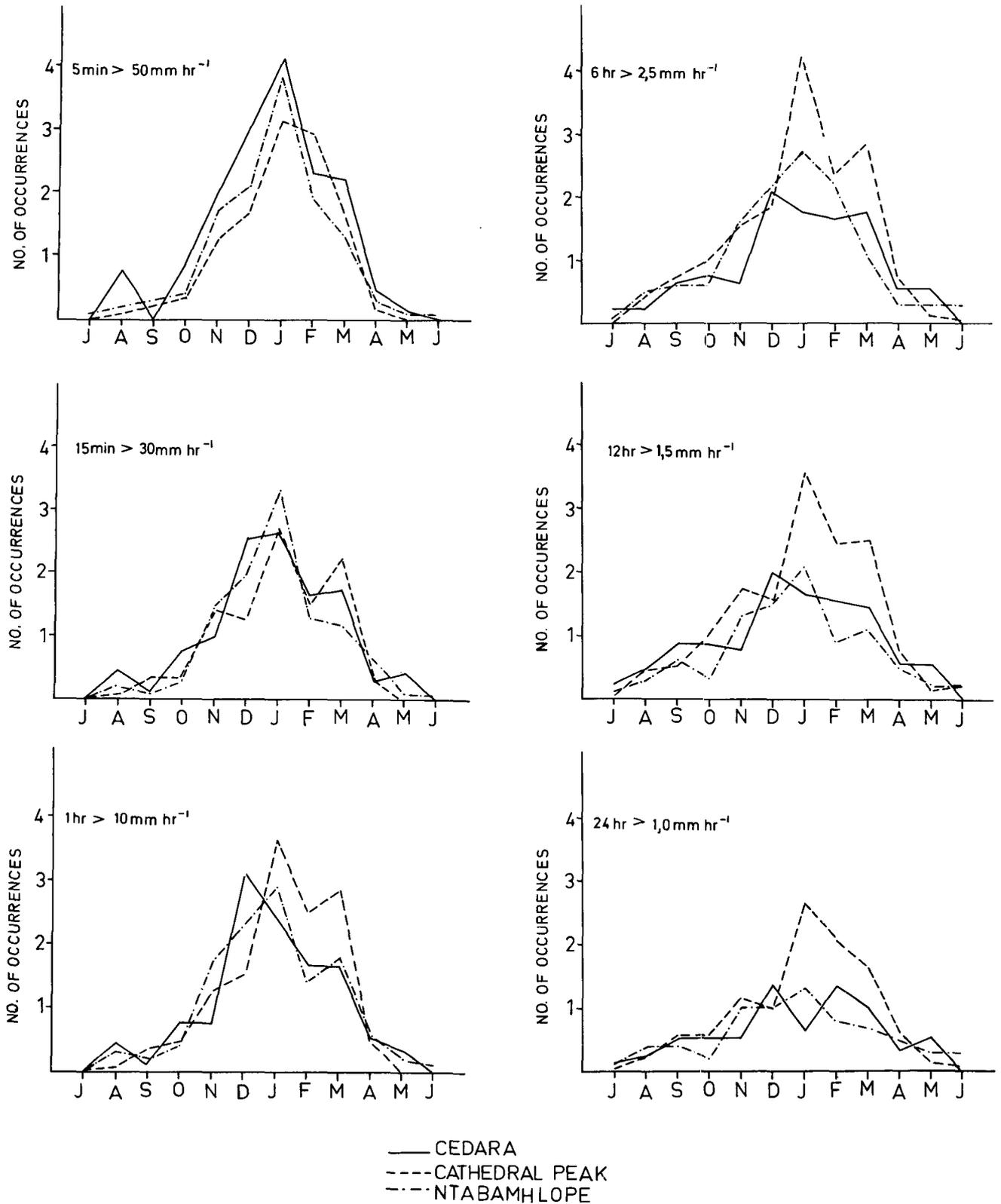*Maximum expected rainfall intensity for selected return periods at three*
Natal stations

Figure 2
Frequencies of occurrence of extreme rainfall events above threshold intensities for selected durations at three Natal stations
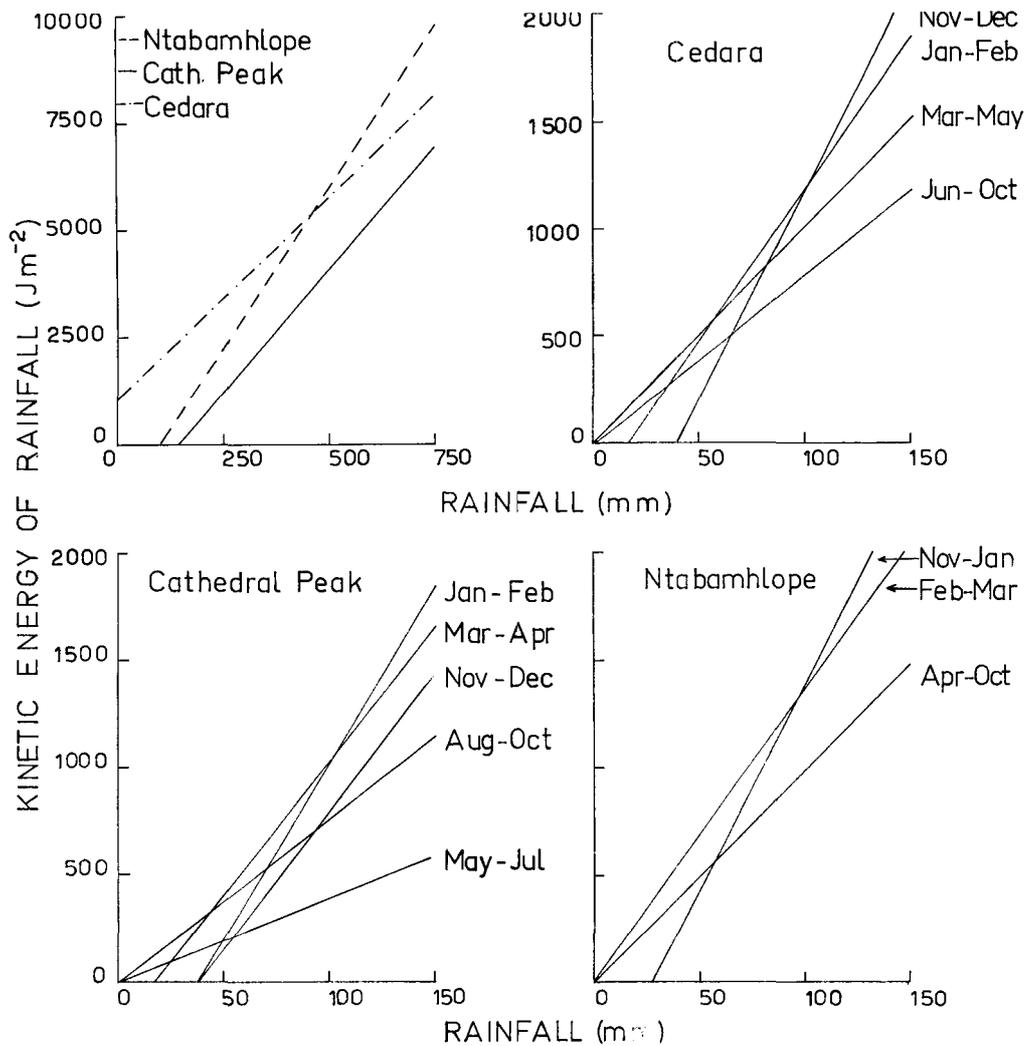
Figure 3
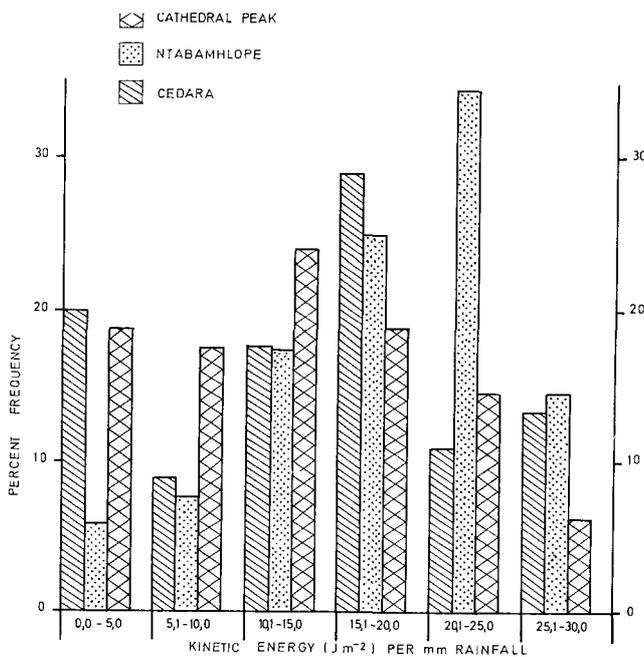*Rainfall: Kinetic energy relationships at three Natal stations*

Figure 4
The frequency distribution of kinetic energy per unit of rainfall for storms of 20 to 30 mm at three Natal stations

characteristics of the rainfall intensity regime can be determined from such KE studies.

When used in stormflow simulation modelling, it is considered that a storm's KE value, because it represents an integrated form of the intensity distribution, is at least as good a rainfall variable to use as, say, peak intensity or mean intensity.

Considerable research interest is also presently focused on the assessment of KE relationships with rainfall, as this energy is an important input into soil loss estimation models such as the Universal Soil Loss Equation, research into which is being carried out in the Unit at the moment.

Analyses from Daily Rainfall Records

Background

Daily rainfall records are kept or have in the past been kept at over 3 000 locations in South Africa. These records may be obtained from the S.A. Weather Bureau and other government agencies (e.g. Department of Agricultural Technical Services). For the past decade, and particularly since the establishment of the Unit, a data bank has been built up at the University of
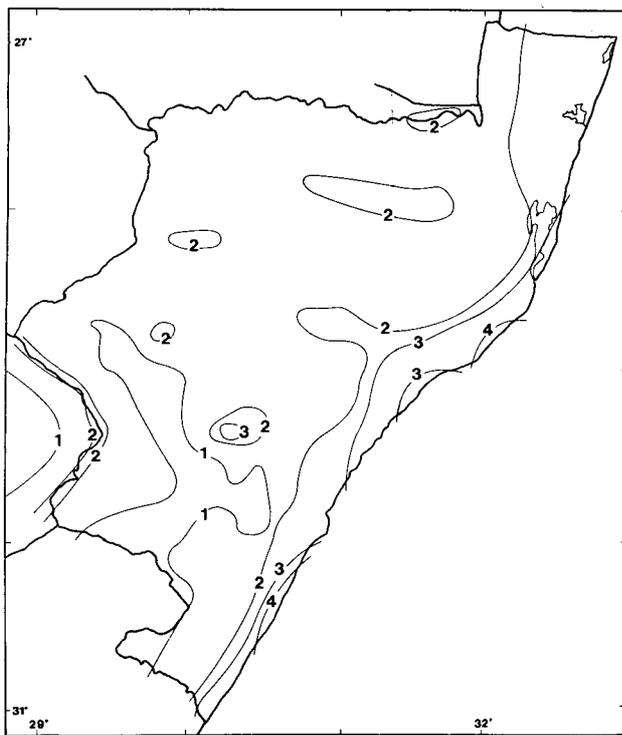
Figure 5
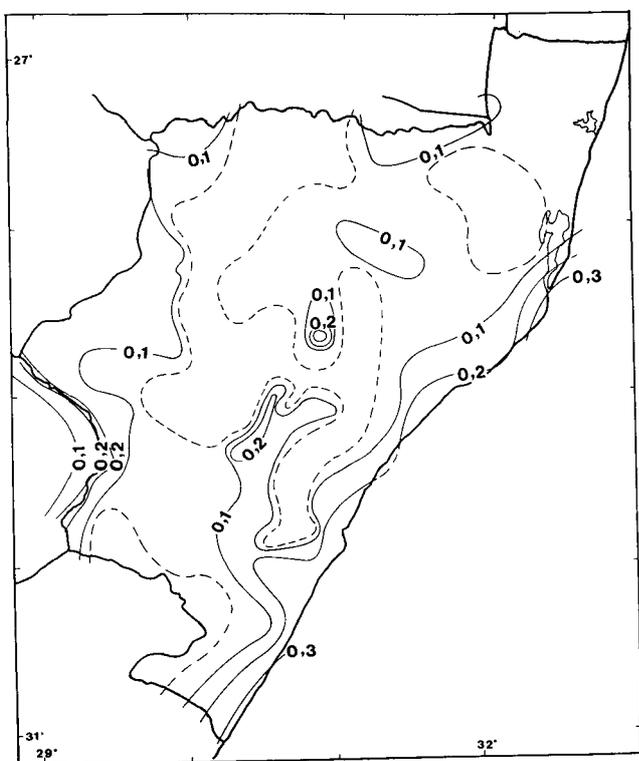*Annual frequency of days with > 50 mm rainfall*

Figure 6
Annual frequency of three consecutive days each with > 25 mm rainfall

Natal in Pietermaritzburg, of daily rainfall records for over 250 Natal stations with medium- to long-term records (>20 years).

A variety of applied rainfall studies are being undertaken by the Unit, using these records. Two categories of this research have been selected for review in this paper, viz. potential flood producing rains studies and drought index studies.

Potential Flood Producing Rains Studies

The 'Tin Town' floods in Durban in 1976 or the devastating floods in Southern Natal in 1959, leaving many homeless, claiming lives and causing millions of Rands worth of damage, were all not the direct result of extreme intensity-short duration events, but rather of rains soaking entire regions' soils to saturation levels for several days on end. How much is actually known about such sustained rains in Natal — about their frequency of occurrence or their magnitudes at given return periods of time? Wiederhold (1969) used 170 long duration (up to 6 days) storms throughout South Africa to determine depth-area-duration relationships for design purposes. Other than that little research had been undertaken in this field of study. This prompted the Unit to embark upon a survey of potential flood producing rains in Natal. Several approaches have been followed in this survey and maps and diagrams have been produced that are hopefully going to be used by planners or engineers.

For convenience a potential flood producing rain has been defined as one in excess of 50 mm d^{-1} or as a series of wet days, e.g. 2 or 3 consecutive days each with more than 25 mm rain. Preliminary maps (Figures 5 and 6) illustrating the distribution of such rains in Natal indicate areas of high or low flood potential.

Another approach to this particular study has been the extraction, on an annual basis, of the highest one, two and seven day rainfall amounts at rainfall stations, then plotting the series on Gumbel extreme probability paper. Examples of such Gumbel plots are illustrated in Figure 7.

For each of some 200 rainfall stations in Natal the values of one, two and seven day expected maximum rainfalls at selected return periods were mapped to ascertain whether regional patterns existed. In Figure 8 it is seen that for a 25 year return period high extremes are a distinct coastal phenomenon, with differences between the coastal and inland stations ranging by up to a factor of 3½. For longer durations (seven days) extreme rainfall probabilities the orographic effect of the Drakensberg becomes evident. Regional differences are not as pronounced, however, as for one and two day events.

In applying the Gumbel technique two problems bear closer examination, viz. the effect the length of a station's record has on the magnitude of extreme events, and secondly, the degree to which a single isolated extreme event (a so-called 'outlier') influences the line of best fit, which is determined by the least squares method.

Stations with relatively long records (>38 years) were analysed as two series with the record split chronologically. Preliminary examination shows no persistent patterns, with some stations displaying marked differences between earlier and later extreme rainfalls, while others showed hardly a difference (Figure 9). This particular facet of extreme rainfall research, however, still requires considerable attention.

In regard to the effect of single, isolated extreme events, the influence of the May, 1959 rains in Southern Natal, which ultimately claimed over 50 lives, was tested. It was found that the effect of this one 'outlier' was most significant in the inland

RETURN PERIOD (YEARS)

DURBAN BOT GARDEN
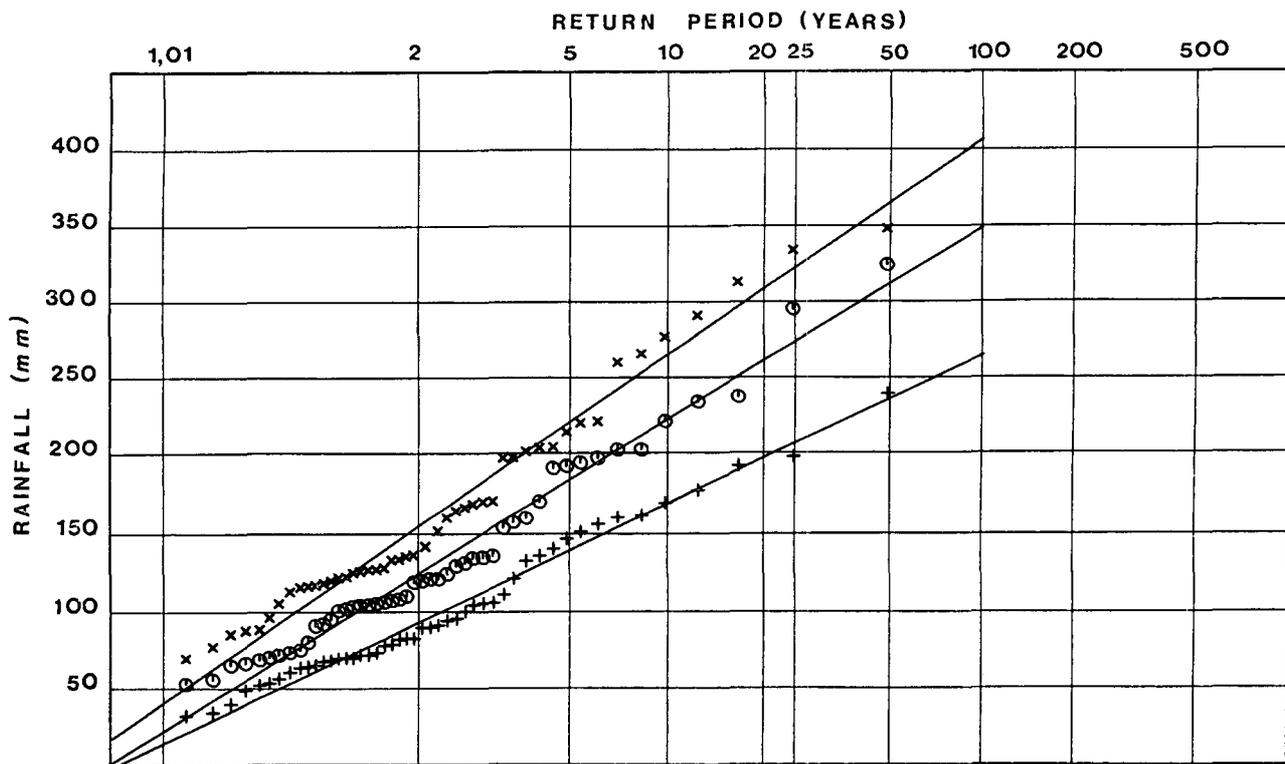
RETURN PERIOD (YEARS)
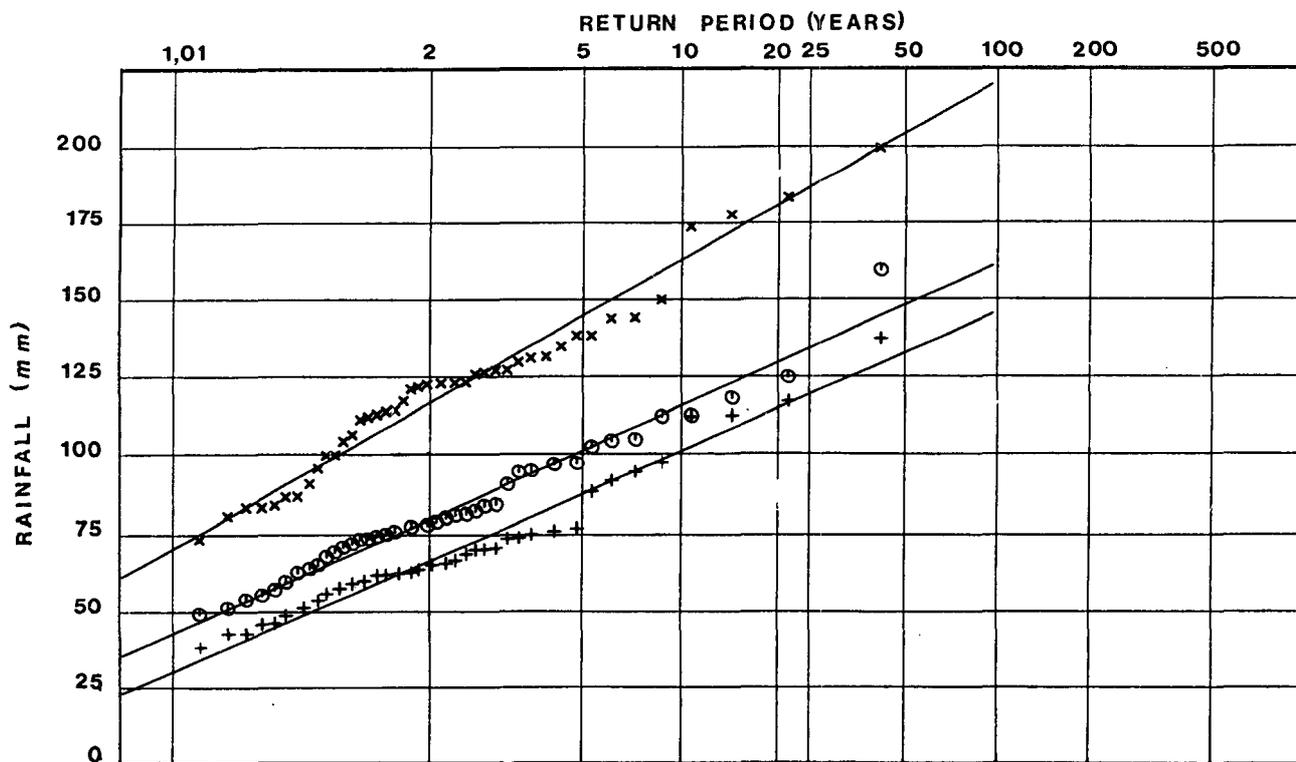
BALLENGEICH

Figure 7

Examples from two stations of one (+), two (o) and seven (x) day expected maximum rainfalls for selected return periods
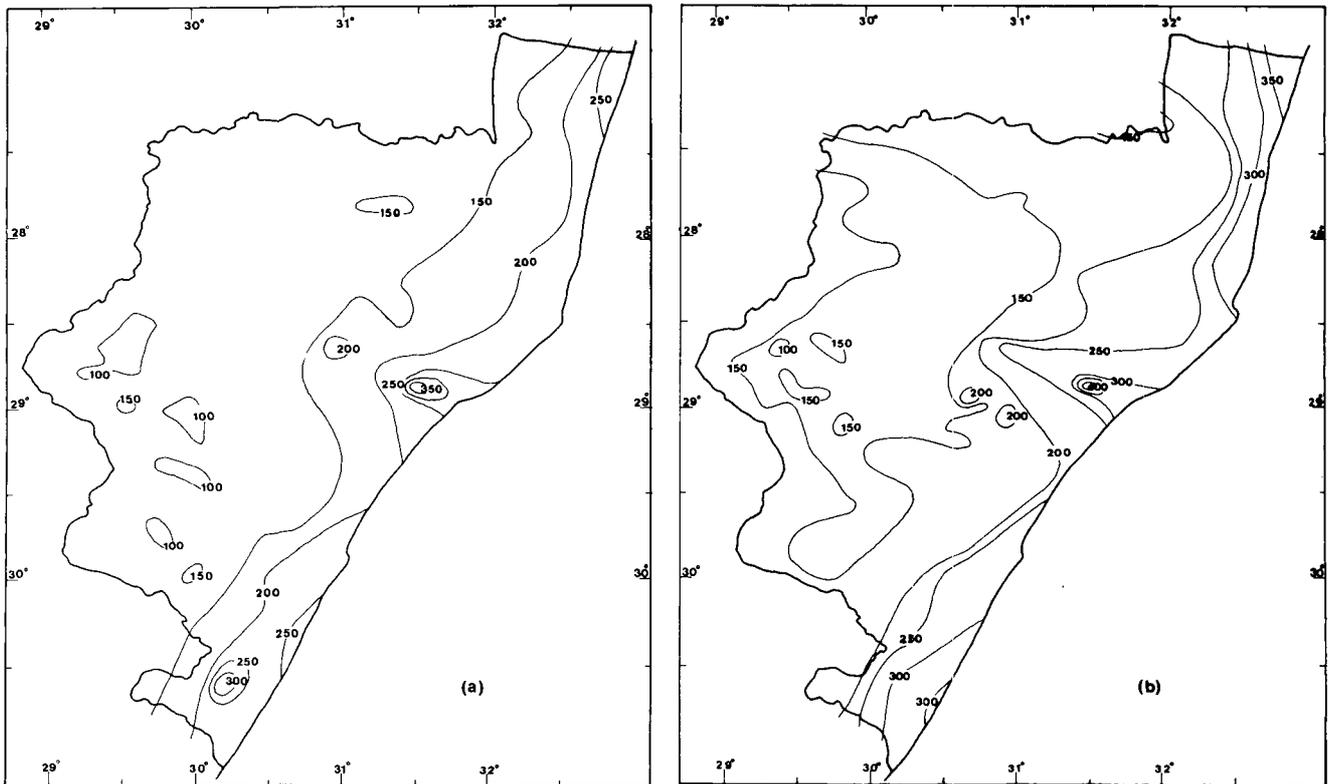
Figure 8
The distribution of expected maximum one (a), two (b) and seven (c)
day rainfall amounts in Natal for a return period of 25 years

regions where relatively low magnitudes of extreme rainfalls are recorded, while the 1959 rains had little influence on the extreme rainfall series at the coastal stations where high rainfall amounts are frequently recorded (Figure 10), but where, in fact, most of the flood damage was incurred.

Drought Indices and Sequences of Low Rainfall

Droughts are difficult to define — indeed, there is no universally accepted definition of the drought phenomenon, for one has to differentiate between agricultural droughts, meteorological droughts or hydrological droughts.

Agricultural droughts, defined as a three-week period with less than 25 mm rain in the grain filling stage of cereals, which in the case of maize is from January 1 to April 30, have been mapped for 120 stations in Natal (De Jager and Schulze, 1977). One such drought can reduce potential maize yields by up to 20%. Figure 11 shows the distribution of drought risk areas in Natal. It may be seen that the annual frequency of the above defined droughts ranges from less than one to more than 3,5. Maps such as Figure 11 are considered most important to agronomists in selecting crops for a region from the viewpoint of rainfall climatology.
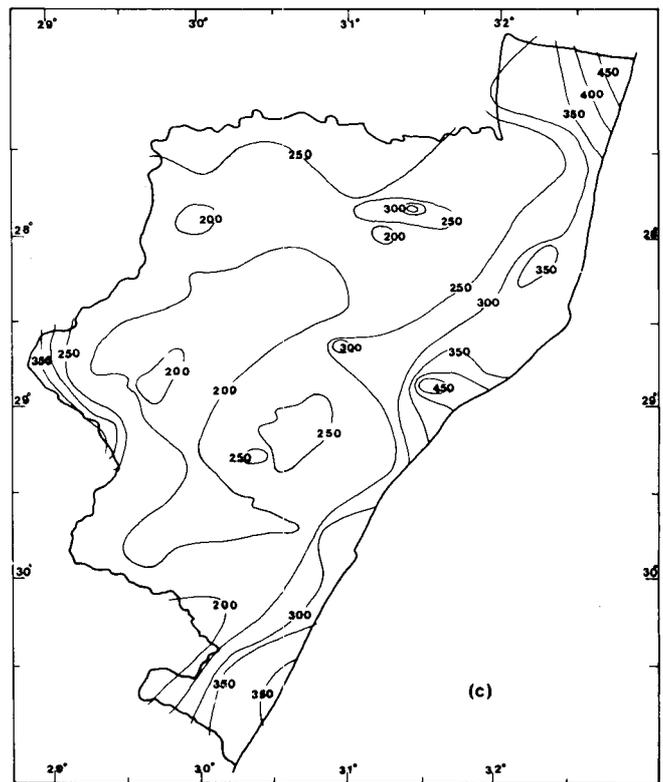
Shorter periods of dry spells may be less dramatic in terms of economic losses, but nevertheless important in planning of agricultural and water resources operations like irrigation scheduling (De Jager and Schulze, 1977). Examples of the distribution of such less intense dry spells are afforded by Figure 12, which shows respectively the frequency of occurrence of 6 or more consecutive and 12 or more consecutive dry days. The
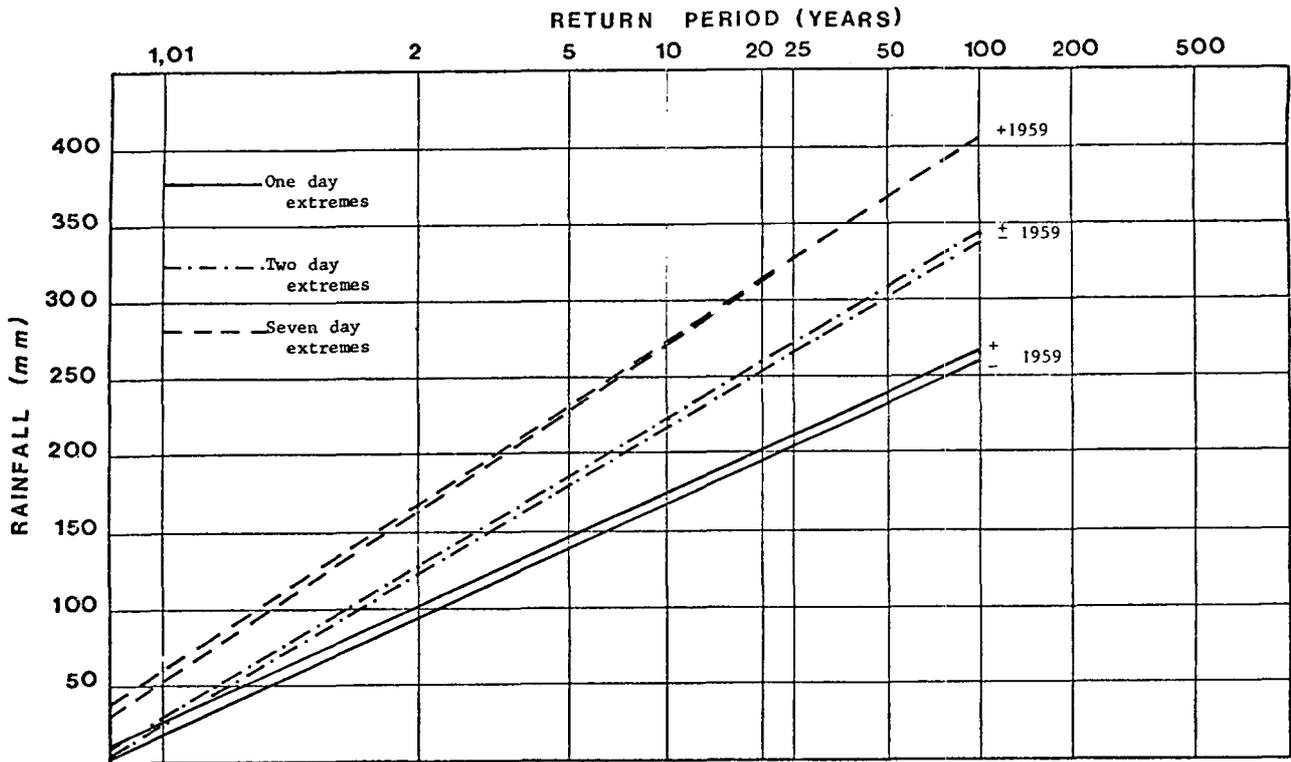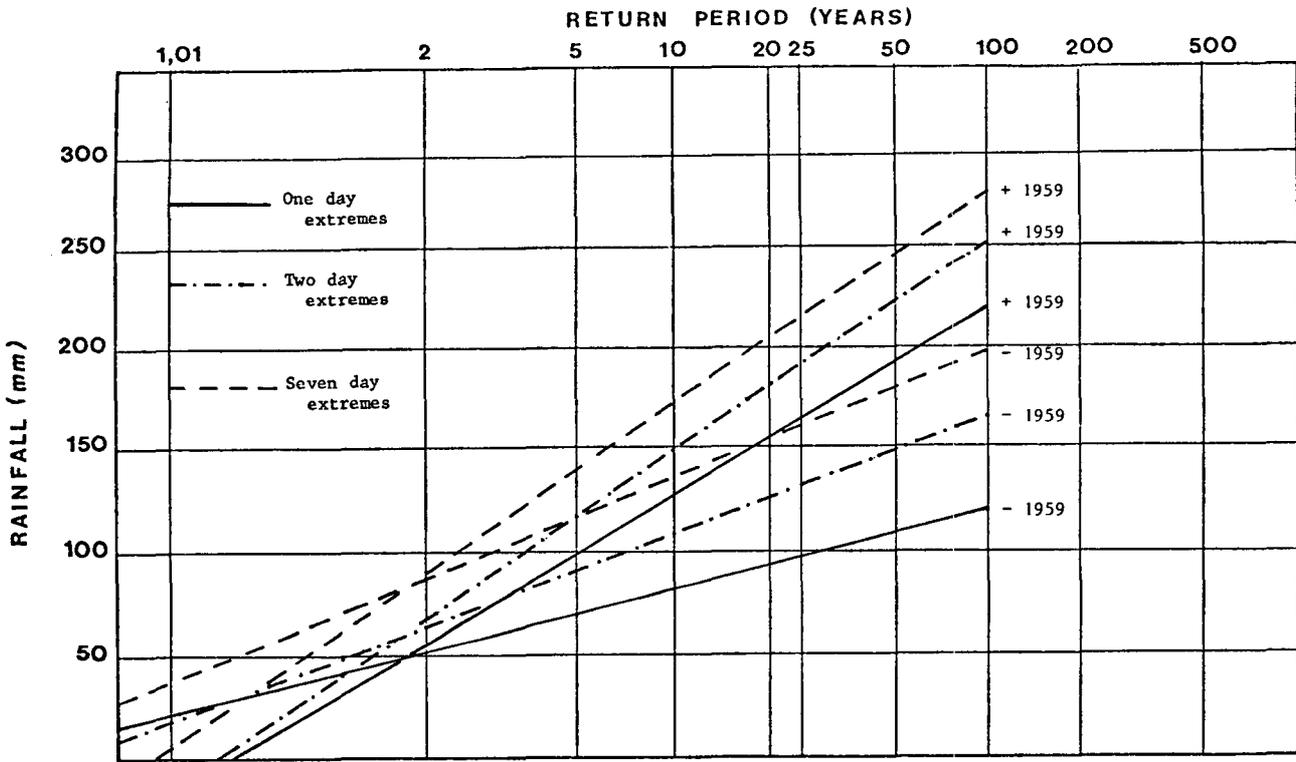
RETURN PERIOD (YEARS)

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RETURN PERIOD (YEARS)
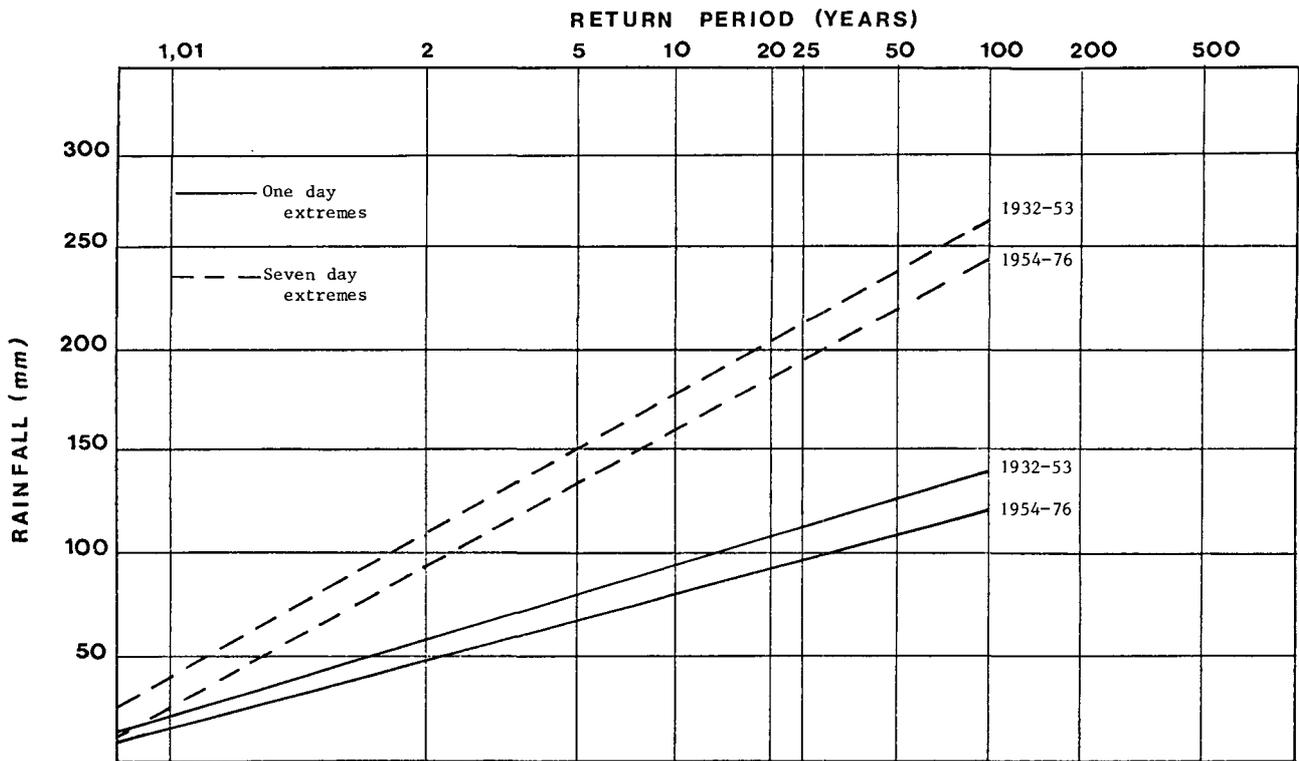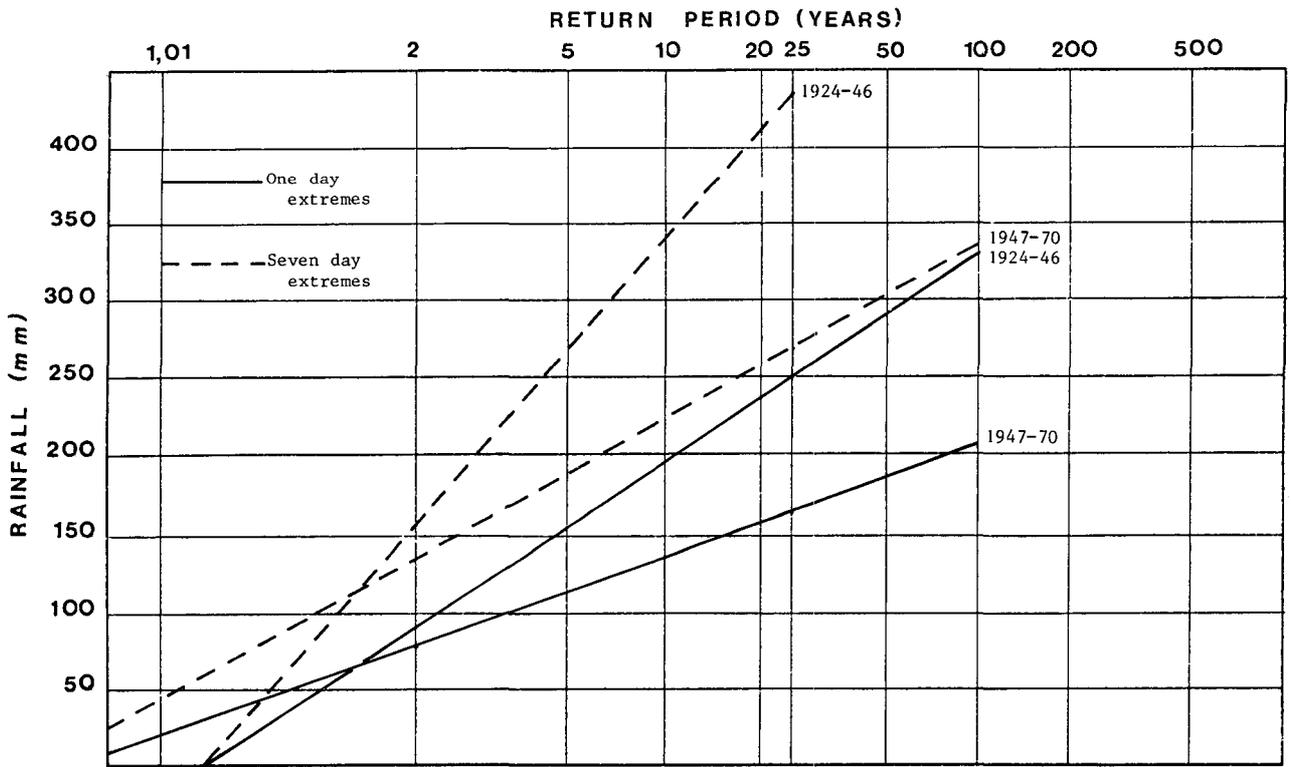
KWAYANA

Figure 9
Examples from two stations of the effect of the period of record on pro-
bable extreme rainfalls

RETURN PERIOD (YEARS)

Chart 1:

Y-axis: RAINFALL (mm) — 400, 350, 300, 250, 200, 150, 100, 50

X-axis (RETURN PERIOD YEARS): 1,01, 2, 5, 10, 20 25, 50, 100, 200, 500

Legend:
- —— One day extremes
- —·—·— Two day extremes
- — — — Seven day extremes

Annotations: +1959, ± 1959, + 1959

PORT SHEPSTONE

RETURN PERIOD (YEARS)

Chart 2:

Y-axis: RAINFALL (mm) — 300, 250, 200, 150, 100, 50

X-axis (RETURN PERIOD YEARS): 1,01, 2, 5, 10, 20 25, 50, 100, 200, 500

Legend:
- —— One day extremes
- —·—·— Two day extremes
- — — — Seven day extremes

Annotations: + 1959, + 1959, + 1959, – 1959, – 1959, – 1959

ESTON

Figure 10
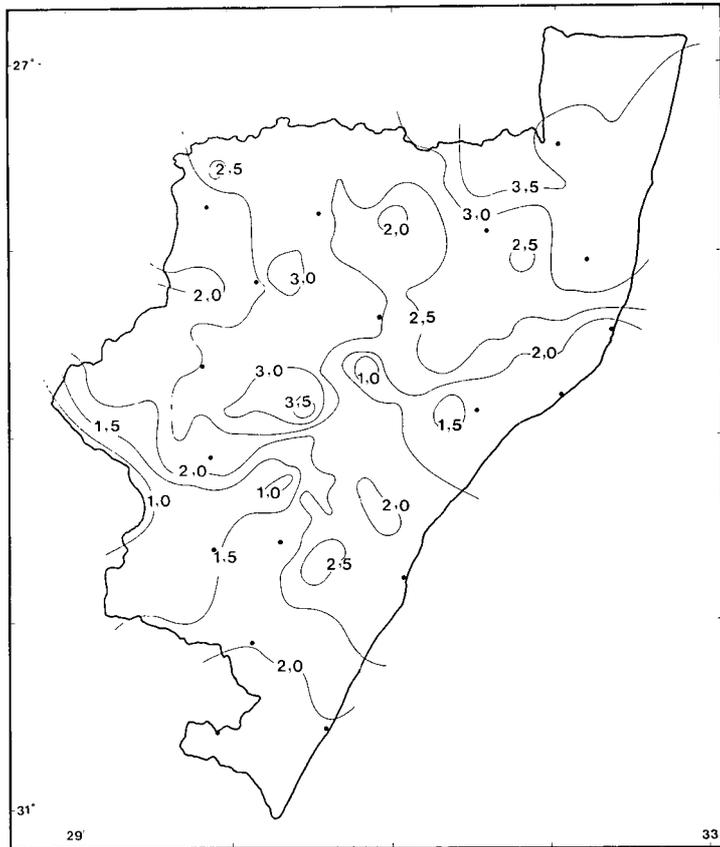The effect of an outlier (the May 1959 rains) on plots of probable extreme rainfalls at two stations

Figure 11
Annual frequency of agricultural droughts occurring in Natal from
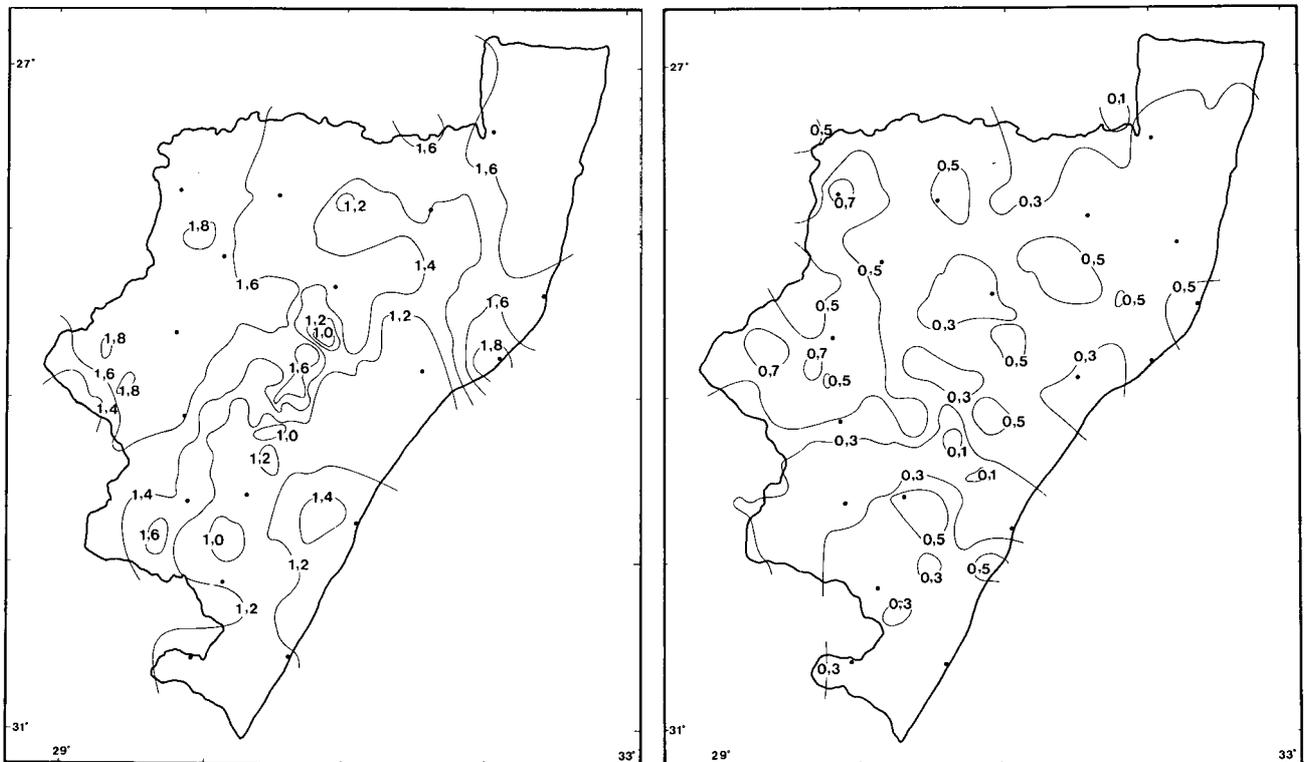*January 1 to April 30 (De Jager and Schulze, 1977)*

Figure 12
ᵢ ne frequency of 6 or more consecutive dry days (left) and of 12 or more
consecutive dry days (right) in Natal in October (De Jager and Schulze,
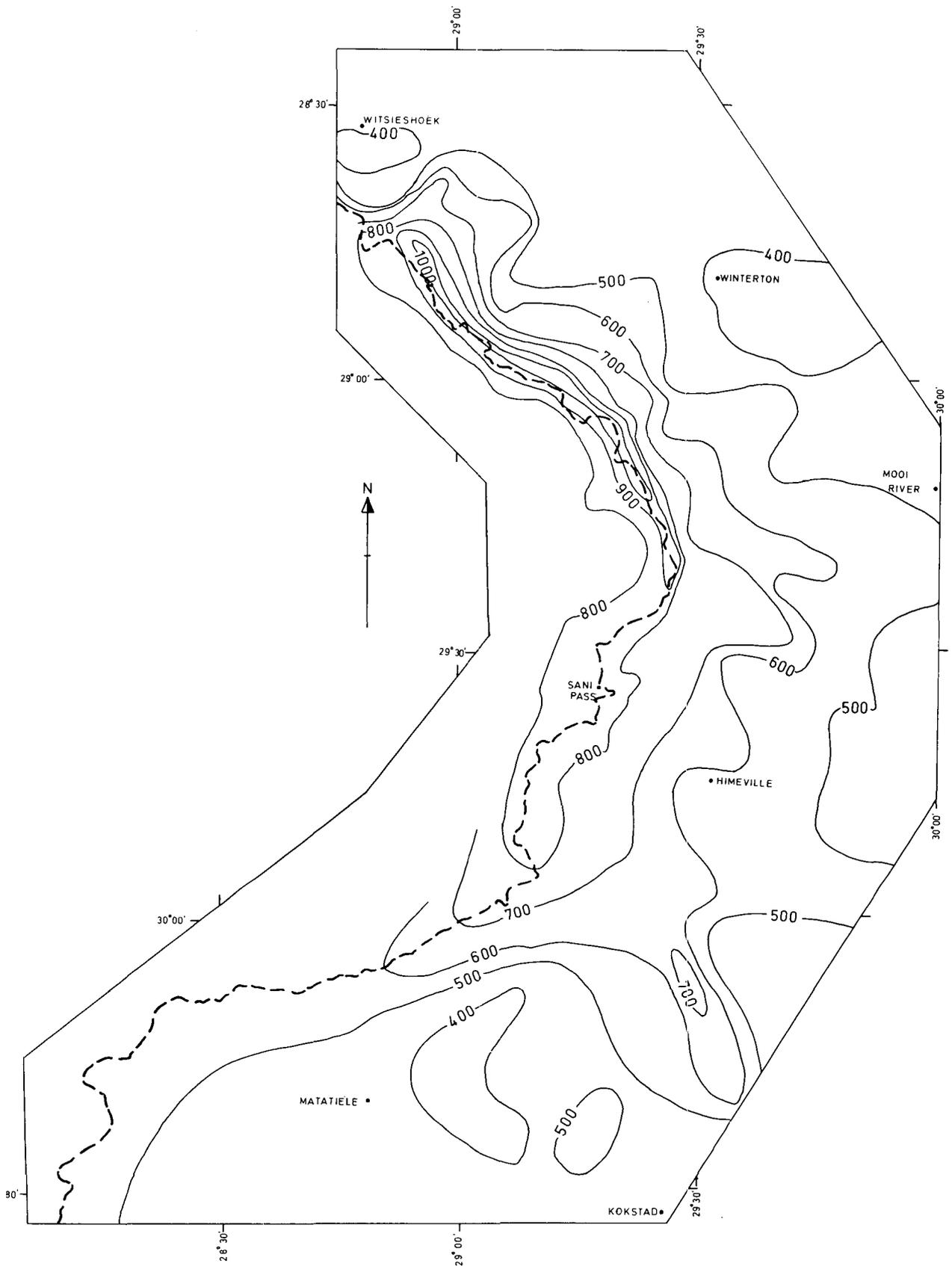*1977)*

Figure 13
Delimination of wet season (October — March) rainfall indicative of
severe drought conditions (i.e. first decile) along the Drakensberg range