



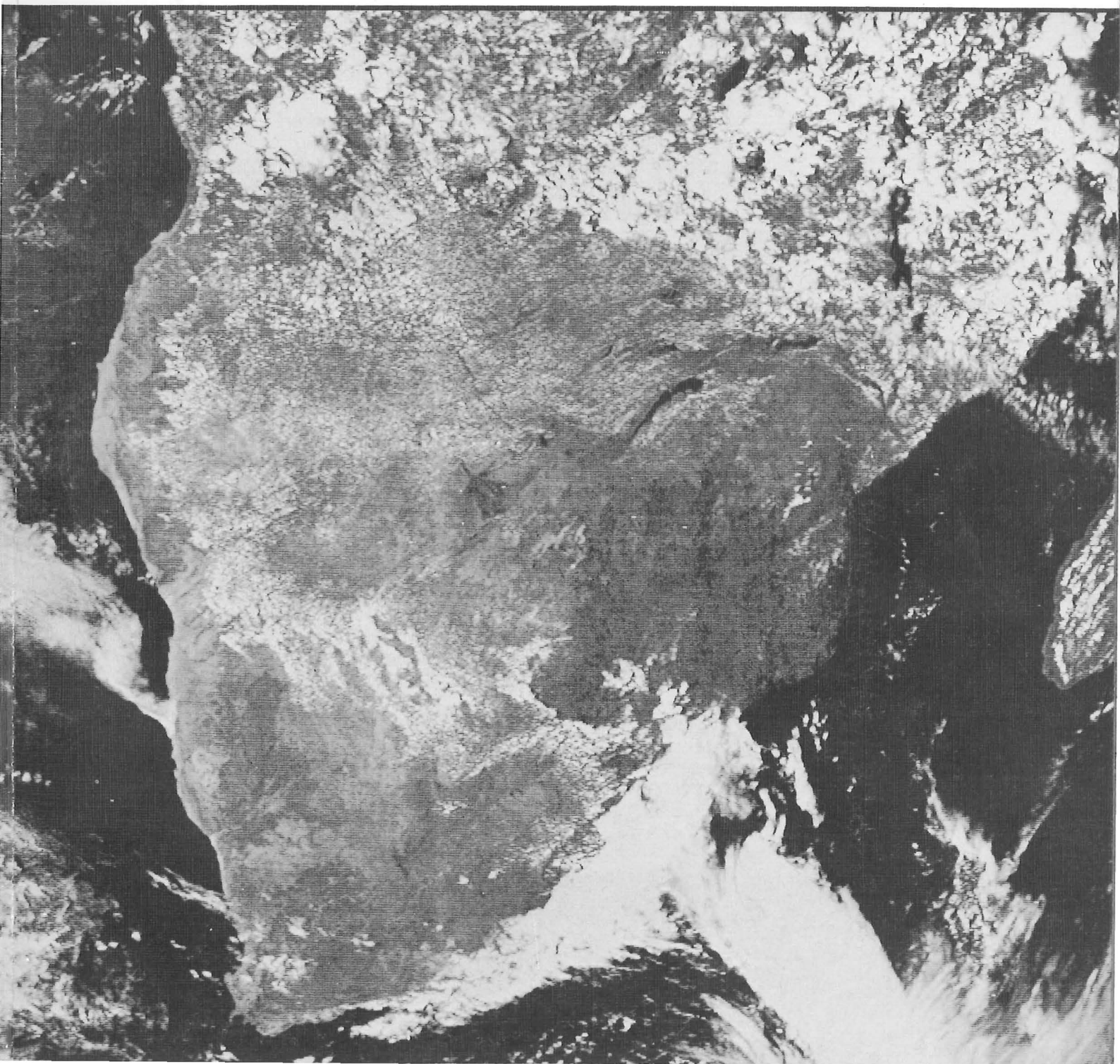
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## Southern African storm rainfall

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SOUTHERN AFRICAN STORM RAINFALL

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## FOREWORD

The primary objective of this report is to present tabulated estimates of extreme n-day rainfalls for South Africa and South West Africa/Namibia with their associated risk. Additionally a means is presented for the computation of short duration storm depths. The statistical procedure employed is relatively untried in the field of hydrometeorological extreme value analysis but provides creditable results in the statistical and physical sense. The validation of the theory is detailed in a separate study.

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\* FRANCIS, D.M. 1980. : The Run-Hydrograph Applied. *Unpublished Masters Thesis. Department of Civil Engineering, University of Natal. King George V Avenue. Durban.*

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## PART I

### 1.1 INTRODUCTION

The design of hydraulic structures and drainage schemes, the evaluation of flood risk and the economic assessment of flood damage to river works, property and crops all require the determination of extreme storm depths. The chance associated with such rainfalls and its calculation for various durations has long provided the hydrologist and engineer with a considerable problem since imposing volumes of data are involved whilst the statistical literature on the subject of extremes as applied in hydrology and meteorology is copious, confusing and conflicting. As a consequence the practising engineer for the most part continues to rely on well-tried but often crude methodologies whilst the many theoretical advances in extreme value analysis rarely find routine application.

It is not the purpose of this report to replace or censure any existing analytical techniques. Rather it is to present the results of a particular statistical procedure on a scale hitherto unavailable in South Africa. For some 2 400 sites within South Africa and South West Africa/Namibia the  $n$ -day ( $n = 1, 2, 3, \text{ and } 7$ ) estimated storm rainfall depth is tabulated for selected recurrence intervals. No attempt has been made to generalize the results, except in map form for geographical interest. The tables provide the primary purpose of the report although additionally a method is proposed for the estimation of storm depths and their associated risk for events of less than one day in duration. It is important to emphasize at the outset that all of the results presented herein refer to one day rainfalls, that is between gauge observation times of 08h00 to 08h00. Corrected storm depths for any 24 hour period are achieved by multiplying the one day estimate by 1,11.

Finally it is hoped that these results will find use not only in the determination of design storm criteria but will further contribute to the material available for the study of the climatology of Southern Africa.

### 1.2 A REVIEW OF PREVIOUS WORK IN SOUTH AFRICA

The study of depth-duration-frequency (DDF) relationships for South Africa and South West Africa, as indeed for most regions of the world, has always suffered from the paucity of autographic raingauges and the shortness of the records available from them. For South Africa there are only some 62 records at the disposal of the analyst, for South West Africa only 7. In both cases the average number of years of data available is less than 18. As a consequence considerable effort has been directed at the regionalization of results and finding functional DDF relationships. Studies of durations in excess of one day have been limited since they are of more climatological interest although in engineering terms they are of consequence to flood analysis where the time of concentration exceeds 24 hours which is generally so under South African conditions for catchments in excess of 3 500 km<sup>2</sup>.



Given the deficiencies of the autographic raingauge network in failing to provide adequate coverage for confident estimation of storm risk for short durations over the greater part of the sub-continent, the estimate of the 1-day rainfall for a particular recurrence interval assumes considerable importance. Assuming that a respectable functional relationship can be established between one day estimates and those for shorter durations computed from the sparse autographic data a means becomes available for the transfer of results to regions where only daily rainfall totals are available. Over South Africa there are 7 500 daily rainfall records which cover all but a few areas; for South West Africa there are some 570 with data lacking only for the coastal belt and the Caprivi.

Hershfield (13), Hershfield, Weiss and Wilson (15), Hershfield and Wilson (14) and Bell (5) provided the first meaningful generalizations of DDF relationships which were adapted for South African conditions by Reich (27). Fundamentally these studies have concentrated on the search for a linear association between a selected recurrence interval and short duration storm depth on the one hand and meaningful but readily available predictor variables on the other. This relationship, when supplemented enables the estimation of short duration storm depth given the recurrence interval of interest. Alexander (4) has reported the latest such study for South African conditions using the 5-year recurrence interval 60 minute rainfall, the mean of the annual series of maximum daily precipitation amounts and the average number of days per year on which thunder was heard. Once this one value can be efficiently estimated, then any other can be evaluated using a set of ratios refined and tested over many areas of the world by Bell (5). These depend on the observation that extremely heavy rainfall of duration less than 2 hours is usually associated with local convectional instability, the meteorological mechanisms within which are universal.

The realization that the proportion of rainfall extremes associated with migratory cyclonic systems and local convectional instability is a function of storm duration tends to reduce the emphasis upon mean annual rainfall as an indicator of the magnitude of short duration storms. The greater part, if not the total variability of mean annual rainfall over Southern Africa can be accounted for by exposure to cyclonic passage, orographic effects and the degree of 'continentality', the only notable exception being the influence of the Benguela current on the Namibian coast. Consequently it would be expected that extreme rainfalls of one day or more in duration are significantly related to mean annual rainfall but storms of less than two hours duration approach independence of mean annual rainfall. This proposition is given some substance by Alexander (4) who found mean annual rainfall to be the least significant candidate for the prediction of short duration storm rainfall.

In providing a scheme for the estimation of DDF relationships over the sub-continent, Midgley and Pitman (22) did, however, employ mean annual rainfall alone as a predictor variable. This was made necessary by the need to estimate point storm values over durations from 15 minutes to 24 hours, a range of stormlife over which mean annual precipitation may be expected to reveal general significance. The identification and demarcation of different rainfall régimes subsequently made possible the construction of a practical co-axial plot which to date remains the most extensively used means for the calculation of short duration point rainfall depths.

Attempts to regionalize the sparse autographic network currently in existence in South Africa have met with little success. Any similarity between DDF curves is more likely a combination of sampling errors, the effect of outliers and the suitability or otherwise of the theoretical probability model employed to derive them than it is attributable to regional homogeneity. Van Heerden (31), using an essentially subjective grouping scheme, has presented a set of type-curves but the combination of results from widely divergent parts of the region without any meaningful reference to meteorological or physical parameters is intuitively unattractive.

### 1.3 DATA ASSEMBLY

Daily rainfall totals for some 8 000 stations over South Africa and South West Africa with some additional records for Swaziland and Lesotho were made available by the South African Weather Bureau. The data tapes had been previously checked and edited, although sample ratification of the data was carried out throughout the analysis. Gaps within the records were coded and where these reached an intolerable level the station record was rejected.

Preliminary analysis of the data revealed that a record length of forty years or more would provide generous coverage for all but a few areas of South Africa whilst for South West Africa the criterion had to be reduced to twenty years.

### 1.4 SCOPE OF THE ANALYSIS

The primary objective of this study is to furnish estimates of  $n$ -day precipitation depths for various recurrence intervals and for the greater part of South Africa and South West Africa. One, two three and seven day durations are considered to be the most pertinent whilst recurrence intervals to a maximum of 200 years are examined. Beyond this results are inclined to become speculative being significantly associated with the assumptions of the probability model employed. Widely different estimates can result but it becomes difficult to validate any one at the expense of the others in purely statistical terms. Estimation at this level is therefore recommended within the context of the particular problem under examination so that factors other than the purely statistical can be accounted for.

The coverage of this report is intended to allow numerous point estimates of storm risk for any particular region or catchment. These estimates can then be analysed jointly for homogeneity and perhaps weighted or averaged at the discretion of the user. Similarly estimates of storm risk for durations shorter than one day may be made employing the procedure recommended herein and assessed through comparative plots of the results.

In addition to the DDF results mean annual rainfall is computed from the data at each of the 2 400 points selected for analysis. Supplementary statistics also include the maximum  $n$ -day rainfall recorded and the minimum annual maximum  $n$ -day rainfall registered. These indicate the range of data employed in the particular statistical scheme applied.

## PART II

### THEORY OF ANALYSIS

#### 2.1 GENERAL

The profuse literature on the theory of extremes as applied in the fields of hydrology and meteorology is ample testament to the lack of agreement as to suitable and recommendable methods of analysis. That chosen for use here was assessed on a sample of 100 records drawn from the various climatic zones of the sub-continent. The performance of the theory in terms of statistical criteria, the testing of the necessary assumptions and comparative studies with alternative probabilistic models forms the basis for an extensive study published elsewhere (Adamson (2)) and which should be viewed as a mandatory addendum to this report. What is evident from the results contained herein is the regional homogeneity and stability of estimates given the various sample ranges and record lengths available.

As is the case elsewhere, previous South African analyses in the field of geophysical extreme values have concentrated on annual maxima. The popularity of this means of data assembly is almost totally related to its ease rather than to its theoretical efficiency in characterizing extreme value time series. Indeed, for short records the use of annual maxima may represent a considerable loss of available information for the estimation of event probabilities. The alternative is the partial duration series in which the sample is composed of all events above a prescribed level. This truncation level may be of physical or statistical significance but should be high enough to ensure independence between selected events. For example, a flood may be defined as any discharge above bankfull and all such discharges analysed as a partial duration series. Similarly a "storm day" may be defined as one on which the rainfall exceeds 25 mm.

After a preliminary study (2) the censored log-Normal model of a partial duration series was selected for the analysis of extreme  $n$ -day rainfalls. In very simple terms this approach involves the study of the upper tail of the log-Normal distribution which is assumed to fit the empirical frequency distribution of all  $n$ -day rainfall depths greater than 0,25 mm (trace). Given that the tail can be specified as a distribution function in its own right, known as the censored log-Normal, the properties of the tail are used to estimate the parameters of the complete model of rainfall depths and thereby the degree of truncation. With this and the mean number of independent events per year greater than or equal to the truncation level known, the event magnitude for any recurrence interval specified in years can be estimated.

#### 2.1 THEORY

Let  $Q_\alpha$  be the random variable which describes the biggest storm in a particular year and let  $F_\alpha$  be its distribution function, i.e.

$$\text{Probability } \{ Q_\alpha \leq q \} = F_\alpha (q) \quad \dots\dots\dots 1)$$

The  $T$ -year event,  $q_\alpha(T)$ , in the annual maximum sense is defined as the solution to the equation :

$$F_\alpha (q_\alpha(T)) = 1 - \frac{1}{T} \quad \dots\dots\dots 2)$$

that is :

$$q_\alpha(T) = F_\alpha^{-1} (1 - \frac{1}{T}) \quad \dots\dots\dots 3)$$

This event has, by definition, the following relative frequency interpretation. Suppose storms are observed for  $n$ -years and that  $n(q_\alpha(T))$  is the number of years during which the maximum storm exceeds  $q_\alpha(T)$ , then :

$$\lim_{n \rightarrow \infty} \frac{n}{n(q_\alpha(T))} = T \quad \dots\dots\dots 4)$$

There will be years during which more than one storm exceeds  $q_\alpha(T)$ , but even for such years  $n(q_\alpha(T))$  is only incremented by one. In other words : on average in one year out of  $T$  there is at least one storm which exceeds  $q_\alpha(T)$ .

For a partial duration series a random variable  $Q_o$  is defined as an event exceeding a given quantity  $q_o$  and that there are, on average,  $\lambda_o$  events  $> q_o$  per year.

Consequently 3) above becomes :-

$$q_o(T) = F_o^{-1} (1 - \frac{1}{T \lambda_o}) \quad \dots\dots\dots 5)$$

where  $F_o (q) = \text{Probability } \{ Q_o \leq q \} \quad q > q_o \quad \dots\dots\dots 6)$

The relative frequency interpretation of  $q_o(T)$  is different from that of  $q_\alpha(T)$  being : if storms are observed for  $n$  years and  $n(q_o(T))$  is the number of storms which occur then :

$$\lim_{n \rightarrow \infty} \frac{n}{n(q_o(T))} = T \quad \dots\dots\dots 7)$$

In this case every storm is counted and on average, once every  $T$  years there will be a storm which exceeds  $q_o(T)$ .

Although  $q_o(T)$  is the more natural measure of the " $T$ -year event" from a partial duration series, most results are based on  $q_\alpha(T)$  and involve a translation of  $q_o(T)$  into  $q_\alpha(T)$ . The following derivation follows this pattern.

Define  $p_o(m)$  as the probability function of the number of storms in which the rainfall exceeds  $q_o$  in a year. Then :-

$$Q_a \leq q_o \text{ with probability } p_o(0) \dots\dots\dots 8a)$$

and  $F_a(q) = \sum_{m=0}^{\infty} p_o(m) F_o(q)^m \text{ for } q > q_o \dots\dots\dots 8b)$

Proof : (Zucchini, personal communication).

There is, by definition of  $p_o(m)$ , a probability equal to  $p_o(0)$  that there are no storms, in which case  $Q_a \leq q_o$ .

Given that  $m$  storms occur in a particular year the distribution of the biggest one is simply  $F_o(q)^m$ ,  $q > q_o$ . Now

$$F_a(q) = p \{ Q_a \leq q \} = \sum_{m=0}^{\infty} p \{ m \text{ storms} \} \cdot p \{ \text{Max storm} \leq q/m \}$$

$$\text{storms} \} = \sum_{m=0}^{\infty} p_o(m) F_o(q)^m$$

If the process describing the arrival of events is Poisson, i.e.

$$p_o(m) = \frac{\lambda_o^m}{m!} e^{-\lambda_o} \dots\dots\dots 9)$$

for  $m = 0, 1, 2 \dots\dots\dots$  then 8b) becomes :-

$$F_a(q) = \sum_{m=0}^{\infty} \frac{\lambda_o^m}{m!} e^{-\lambda_o} F_o(q)^m, \quad q > q_o \dots\dots\dots 10)$$

This sum converges to the result :

$$F_a(q) = e^{-\lambda_o} (1 - F_o(q))^{-\lambda_o}, \quad q > q_o \dots\dots\dots 11)$$

If the exceedences of  $q_o$  are distributed according to the truncated log-Normal model, then

$$F_o(q) = \frac{\Phi((\ln q - \mu)/\sigma) - \Phi(\xi_o)}{1 - \Phi(\xi_o)}, \quad q > q_o \dots\dots\dots 12)$$

Where  $\Phi(\cdot)$  is the distribution function of a standard normal random variable,  $\xi_o$  is the standard normal random variable corresponding to  $q_o$  and  $\mu$  and  $\sigma$  are the mean and standard deviation of  $\ln(q)$  for all  $q > q_o$ . Substitution of 12) into 11) yields :-

$$F_a(q) = e^{-\lambda_0} \left( 1 - \frac{\Phi((\ln q - \mu)/\sigma) - \Phi(\xi_0)}{1 - \Phi(\xi_0)} \right), \quad q > q_0 \quad \dots\dots\dots 13)$$

or

$$F_a(q) = e^{-\lambda_0} \left( \frac{1 - \Phi((\ln q - \mu)/\sigma)}{1 - \Phi(\xi_0)} \right), \quad q > q_0 \quad \dots\dots\dots 14)$$

The  $T$  year event  $q_a(T)$  can now be found by recalling equation 2) :-

$$1 - \frac{1}{T} = \exp \left\{ -\lambda_0 \left[ 1 - \Phi \left( \frac{\ln q_a(T) - \mu}{\sigma} \right) \right] \right\} / \left[ 1 - \Phi(\xi_0) \right]$$

$$\Rightarrow \Phi \left( \frac{\ln q_a(T) - \mu}{\sigma} \right) = (1 - \Phi(\xi_0)) \cdot \ln \left( 1 - \frac{1}{T} \right) / \lambda_0 + 1$$

$$= x, \text{ say}$$

$$\therefore q_a(T) = e^{Z(x) \sigma + \mu} \quad \dots\dots\dots 15)$$

where  $Z = \Phi(.)^{-1}$  which can be conveniently established using the functional approximation given in Abramovits and Stegun (1) p. 932 . Maximum likelihood estimators of  $\mu$  and  $\sigma$  are given by Cohen (6) as the solution to the equations :-

$$\left[ 1 - \xi_0 (Y - \xi_0) \right] / (Y - \xi_0)^2 - (v_2/v_1^2) = 0$$

$$\hat{\sigma} = v_1 / (Y - \xi_0) \quad \dots\dots\dots 16)$$

where

$$\hat{\mu} = q_0 - \sigma \xi_0$$

$$Y(\xi_0) = \frac{n_2}{n_1} \cdot \frac{\phi(\xi_0)}{1 - \Phi(\xi_0)}$$

and

$$v_K = \frac{n_1}{\sum_{i=1}^{n_1}} (q_i - q_0)^K / n_2 \quad K = 1, 2$$

with  $\phi(.)$  the density function of a standard normal random deviate and  $n_1$  and  $n_2$  describing the number of events  $> q_0$  and  $\leq q_0$  respectively.

### 2.3 COMPUTATION

In the present study the truncation level  $q_0$  was chosen as the minimum annual maximum  $n$ -day point rainfall which results in the partial and annual series having the same range which was found useful for comparative studies (2). For the 2 400 daily rainfall records analysed the degree of truncation  $\Phi(\xi_0)$  was generally found to be in the region of 90% and  $\lambda_0$  usually in the range 4 to 7.

A sample calculation which clarifies the theory is given in Adamson (2).

## PART III

### USE OF TABLES, AREAL REDUCTION OF POINT ESTIMATES, TEMPORAL PROPERTIES OF STORMS AND COMPUTATION OF STORM RISK FOR DURATIONS OF LESS THAN ONE DAY

#### 3.1 USE OF TABLES

Appendices A and B contain the  $n$ -day storm risk estimates for South Africa and South West Africa respectively. They are tabulated using the same numbering scheme for rainfall gauges as used by the Weather Bureau. Each station is identified by a six-digit code which is indicative of its location in terms of latitude and longitude. The first three digits denote the  $\frac{1}{2}^\circ$  by  $\frac{1}{2}^\circ$  square in which the gauge is sited and the second three its sequence within that section. Reference numbers of less than six digits should be prefixed by zeros. Maps of Weather Bureau sector indices may be found in Appendix C for South Africa and Appendix D for South West Africa.

The coverage of point estimates for the greater part of the sub-continent enables storm risk to be evaluated in conjunction with small scale topographic maps so that effects such as altitude, orientation and position can be investigated. Such an exercise is illustrated in Figure 3.1 where for the catchment of Vaal Dam isolines of point storm depth with a recurrence interval of 50 years and duration of one day are shown. In this case some seventy single site estimates were available. Even where coverage is less extensive it is felt that the scope of the analysis enables more than one point estimate of storm risk to be made in any region of interest.

#### 3.2 AREAL REDUCTION OF POINT ESTIMATES

The areal reduction of point rainfall estimates assumes considerable importance in hydrology when mean storm precipitation depth over a catchment area has to be estimated. From this estimate a volume of storm precipitation may be computed for a catchment and used as input to a flood discharge analysis. Usually the relationship between mean depth of rainfall and area is presented as a family of curves with each curve representing a different rainfall duration.

Storm centred relations provide the areal variability of rainfall referred to the storm depth at its centre. Geographically fixed relations are obtained by referring mean areal rainfall depth to that at the centre of a fixed network of rain gauges. In practice it is obvious that areal reduction curves derived from storm centred studies will provide a much faster reduction of mean storm depth with distance than will results derived from geographically centred studies. Generally speaking the difference between mean areal rainfall depth and that recorded at a storm centre :

1. Increases with increasing storm area.
2. Decreases with increasing duration.
3. Is greater for convective and orographic precipitation than for cyclonic, and
4. Increases with a decrease in total rainfall depth.

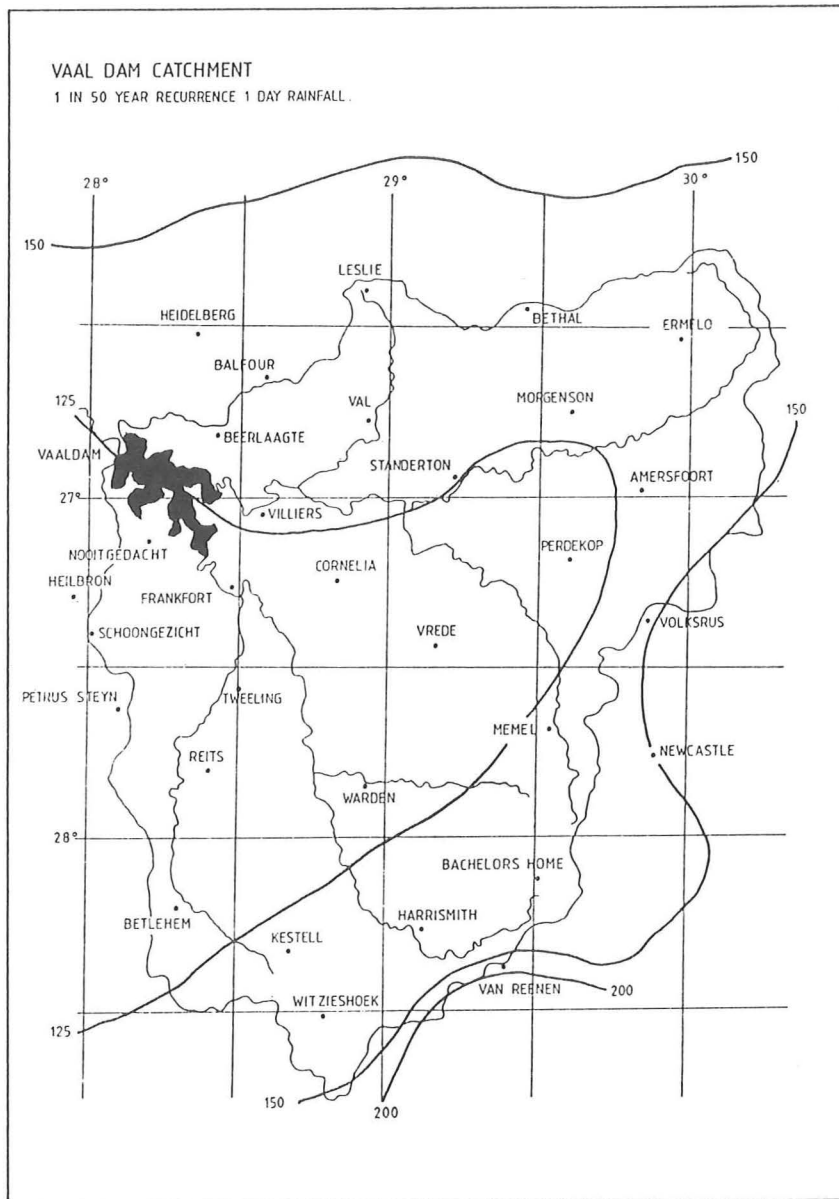


FIGURE 3.1 : AN EXAMPLE OF THE REGIONAL MAPPING OF POINT STORM RISK FROM DATA AVAILABLE IN APPENDICES A AND B.



Many empirical relationships have been proposed for storm centred areal reduction. They are largely conflicting and are generally only applicable to particular storm types. Most of the work has been reviewed and compared by Court (7). Surprisingly, storm centred studies rarely take storm duration into account, a fixed algebraic relationship between area and mean rainfall depth being assumed to apply from a storm life of an hour to a day. Nicks and Igo (25) have recently responded to this omission in an analysis of 138 storms over a dense raingauge network in the Southern Great Plains of the United States. For this Oklohoma region a functional relationship is proposed between the areal reduction factor (ARF), storm duration and area with regression parameters sought by an optimisation scheme. This model is given by :-

$$ARF = 1.0 - \frac{A \cdot D^m}{a + b A} \quad \dots\dots\dots 3.1$$

where  $A$  is the area in square kilometres,  $D$  is storm duration in hours and  $a = 337,5$ ,  $b = 1,1$  and  $m = -0,15$ . The resulting family of curves for selected durations is shown in Figure 3.2. Validation of the model was carried out on a further 203 storms over the Chicago urban area where optimised parameters were found to be insignificantly different from those obtained from the Oklahoma study.

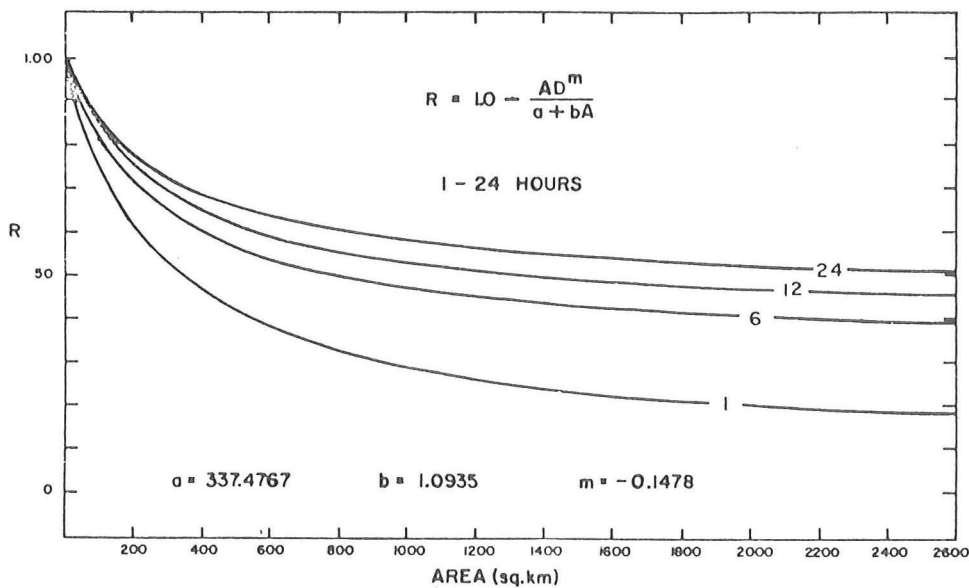


FIGURE 3.2 : SELECTED AREAL REDUCTION CURVES FROM THE RELATIONSHIP PROPOSED BY NICKS AND IGO (25)

The majority of the storms analysed by Nicks and Igo (25) were of the single-centred convectonal air mass type with durations of 30 minutes to 24 hours and maximum point rainfalls of 25 mm to 250 mm. Figure 3.3 shows that the areal decay of mean rainfall depth for extreme single-centred events over Durban, Port Elizabeth and Pretoria is very rapid indeed, a feature which would seem to be characteristic of extreme

thunderstorm rainfall.

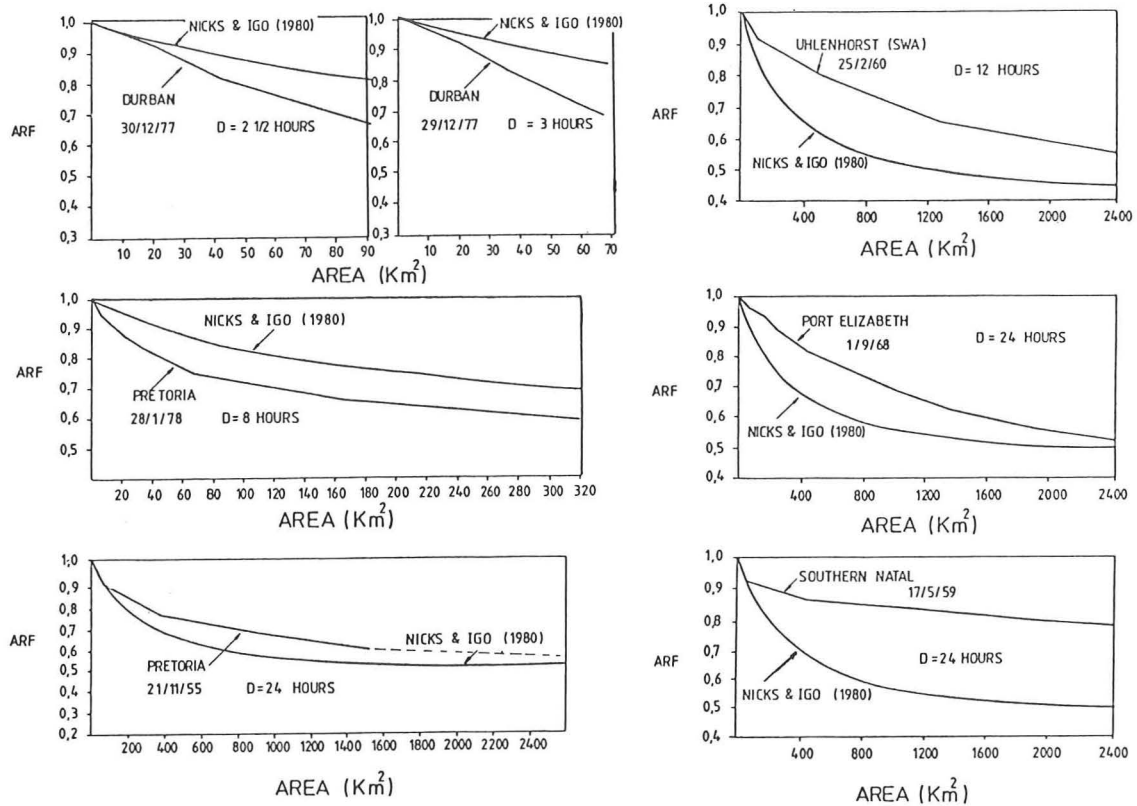


FIGURE 3.3 : SOME COMPARISONS BETWEEN THE STORM CENTRED AREAL REDUCTION OF SELECTED HISTORICAL STORMS AND THE FACTORS PROPOSED BY NICKS AND IGO (25).

Wiederhold (33) and van Wyk and Midgley (32) have presented ARF curves from a study of South African storms. These relationships are storm centred and were computed in the same way as those of Nicks and Igo (25) to produce mean areal rainfall depth. The study of small area, intense storms was confined to the Pretoria region whilst major, large area events were analysed for each of the various regions of the country. The areal decay of mean storm rainfall from this South African data is rather less steep (Figure 3.4) than that found in the Great Plains where storms are generally associated with frontal thunderstorm activity. In comparison the South African study included a considerable number of large area events associated with migratory cyclonic systems for which the characteristic ARF curve would be expected to be relatively less steep.

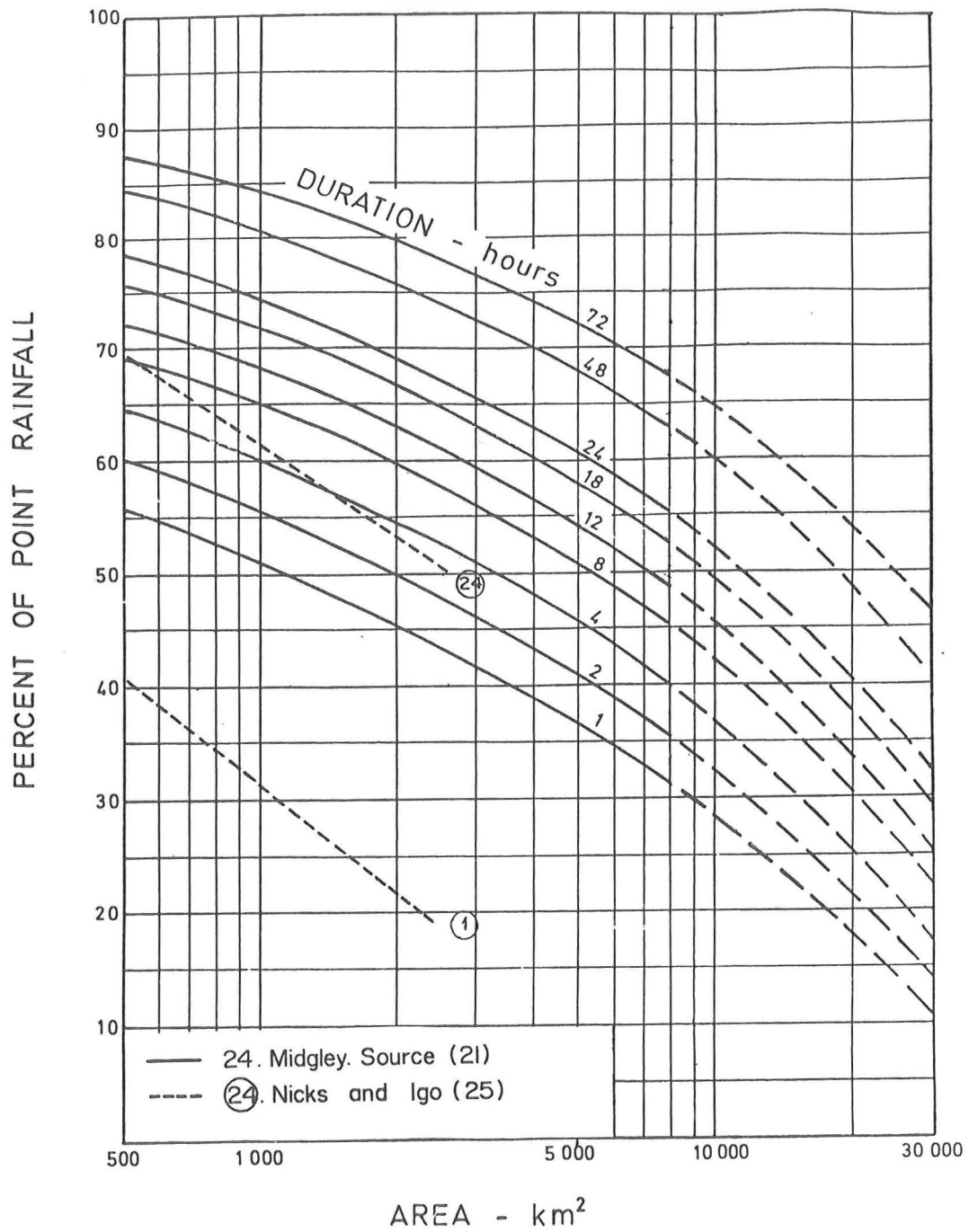


FIGURE 3.4 : COMPARISON OF STORM CENTRED AREAL REDUCTION CURVES PROPOSED BY MIDGLEY (21) FOR SOUTH AFRICA AND THOSE OF NICKS AND IGO FOR THE CENTRAL USA.

Another approach to storm centred areal reduction studies is to compute storm areas on which rainfall depth is equalled or exceeded. This scheme has been followed by Hershfield and Wilson (14) in a study of 153 storms over the eastern and southern United States. The resulting ARF curves are considerably shallower (cf. Figure 3.5) and would give large overestimates of mean areal storm rainfall if used erroneously. In fact their value lies less in the field of design storm determination than in the investigation of the areal properties of different synoptic storm types.

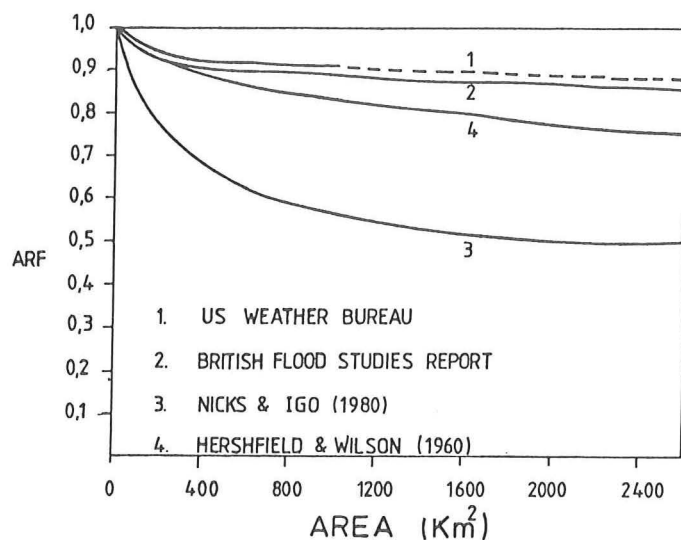


FIGURE 3.5 : COMPARATIVE AREAL REDUCTION CURVES FOR ONE-DAY STORMS.

Geographically fixed areal reduction relationships are not as sensitive to synoptic storm type and indications are that regionally they are reasonably stable. Certainly the similarity between the United States and United Kingdom results (cf. Figures 3.5 and 3.6) is remarkable whilst within widely divergent regions of the latter no significant difference in the curves was found (24). The United States results are recommended for standard design storm practice in Australia (18) for flat areas of up to 1 000 km<sup>2</sup>. In South Africa, for design events associated with large scale migratory rainfall generating systems such as those responsible for the Laingsburg disaster of 1981, the Karoo floods of 1961 and 1974 or those of 1959 in southern Natal it is felt that these geographically centred results are appropriate. For such events the duration of the complete storm becomes protracted, perhaps amounting to several days such that total storm volume becomes critical over vast areas. The area-time structure of such events tends to become complex and varied such that the areal decay from maximum point rainfall depth is characteristically shallow.

The following recommendations for the practical application of the areal reduction of point rainfall depths in Southern Africa are proposed.

1. Storm centred curves (Nicks and Igo; van Wyk and Midgley). Appropriate to the typical urban design storm problem over small catchments and for storms of less than 12 hours duration. Synoptically the curves of Nicks and Igo should only be

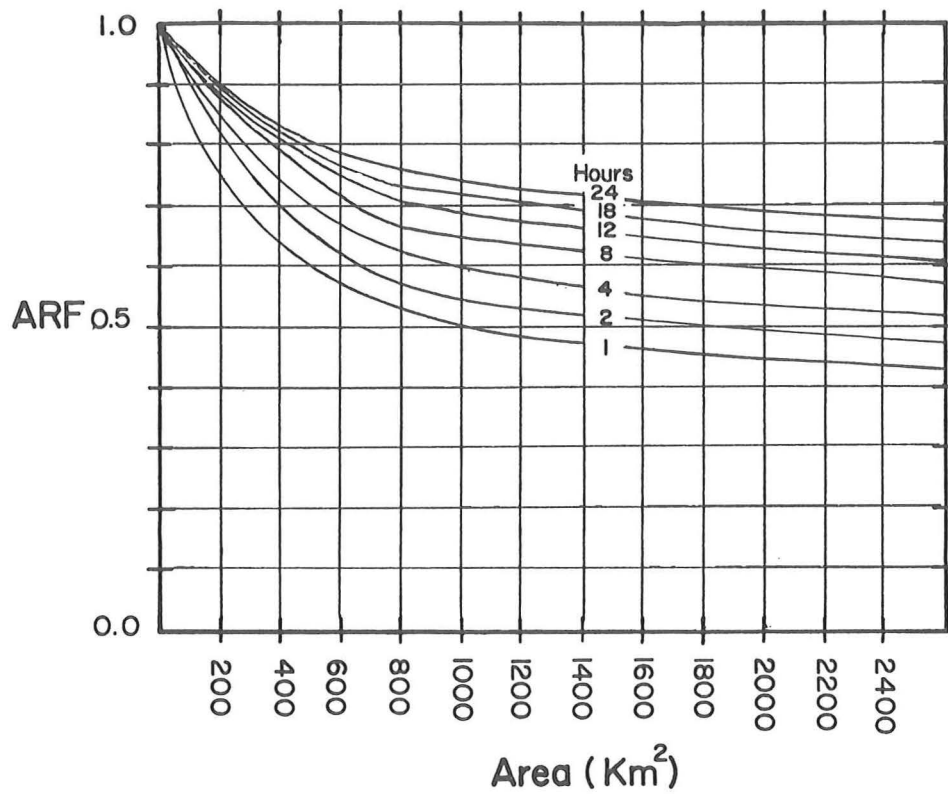


FIGURE 3.6(A) : ARF CURVES PROPOSED BY THE BRITISH FLOOD STUDIES GROUP - SOURCE (24)

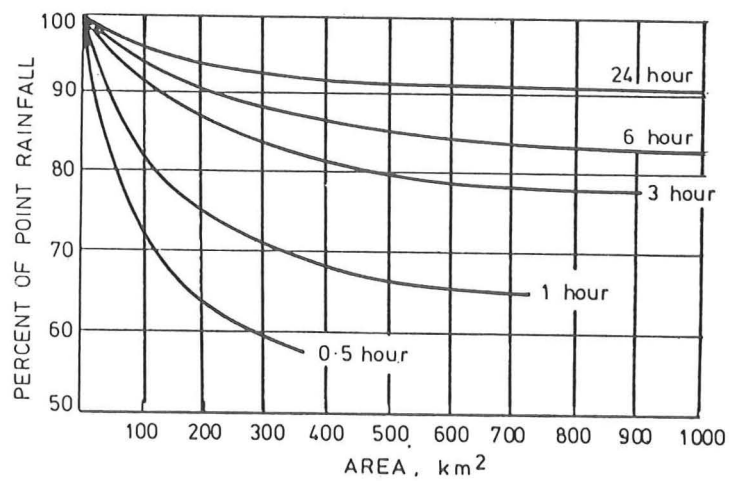


FIGURE 3.6(B) : ARF CURVES PROPOSED BY THE U.S. WEATHER BUREAU - SOURCE (18).

NOTE

FIGURE 3.6(A) page 14

An incorrect diagram has been inserted for the NERC 'ARF' factors.  
The correct ratios are as below :

DURATION	AREA (km <sup>2</sup> )							
	1	5	10	30	100	300	1000	3000
1 hour	0,96	0,93	0,91	0,86	0,79	0,71	0,62	0,53
2 hours	0,97	0,95	0,93	0,90	0,84	0,79	0,73	0,65
3 hours	0,97	0,96	0,94	0,91	0,87	0,83	0,78	0,71
6 hours	0,98	0,97	0,96	0,93	0,90	0,87	0,83	0,79
24 hours	0,99	0,98	0,97	0,96	0,94	0,92	0,89	0,86

FIGURE 3.6(A) : ARF CURVES PROPOSED BY THE BRITISH FLOOD STUDIES GROUP - SOURCE (24)

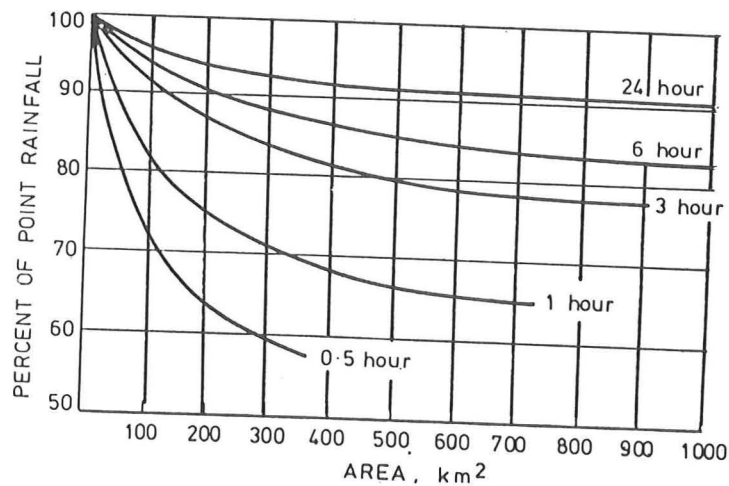


FIGURE 3.6(B) : ARF CURVES PROPOSED BY THE U.S. WEATHER BUREAU - SOURCE (18).

associated with air-mass thunderstorms whilst both relationships are consistent with the assumption of spatially uniform rainfall depth as required in linear unit hydrograph theory.

2. Geographically fixed curves. (United States Weather Bureau; United Kingdom Flood Studies Report).

Appropriate to design storms for larger catchments of over 1 000 km<sup>2</sup> and storm durations of more than 12 hours. Both results are consistent with assumptions of spatially uniform rainfall depth.

Application of ARF curves should be confined to relatively flat regions. For mountainous areas and regions where topographic effects on storm patterns are evident supplementary meteorological information is required before storm areal patterns can be synthesized.

In none of the studies reported above has any correction been made for the effects of the speed and direction of storm movement on the areal patterns of rainfall depth. Obviously in regions where storms follow a dominant track the pattern of isohyets should not be assumed to be circular. Insight into these properties of storm rainfall patterns is being pursued through radar studies.

### 3.3 TIME PROFILES OF POINT RAINFALL

The temporal properties of storms and rainfall bursts are important for the assessment of the flood generating potential of precipitation events, the design of urban storm drainage systems and even in the understanding of soil erosion processes. Storm time profiles are usually presented as mass curves in which the cumulative percentage of total storm rainfall is plotted against cumulative percent total storm duration. Four examples are shown in Figure 3.7, numbers one to three showing typical time distributions for rainfall from air-mass thunderstorms and the fourth that of a more complex system of rainfall events of over 42 hours. Such is the diversity of the pattern it is most unlikely that a characteristic time profile for storms of a given type, duration or area can be found. This point is confirmed by Van Wyk and Midgley (32) from a study of temporal storm patterns over the Pretoria area. For design purposes their solution was to present the lower envelope boundary of these storms on the assumption that the critical temporal pattern of storm behaviour for design purposes is that for which rainfall intensity is a maximum in the last third or quartile of the storm. A short study of South African storm profiles was made by Hofmeyr and Nagel (16) who compared the characteristic pluviographs for Cape Town and Pretoria. Figure 3.8 shows that for Cape Town storms producing in excess of 20 mm and usually associated with approaching cold-fronts start off very gradually and increase to a steady rainfall. On the other hand Pretoria storms of the characteristic convective type start off quite rapidly and with very much the greater part of the rain falling in the first half of the event.

The most extensive and potentially useful study of this aspect of storm rainfall is that of Huff (17) using a dense network of gauges in East Central Illinois from which

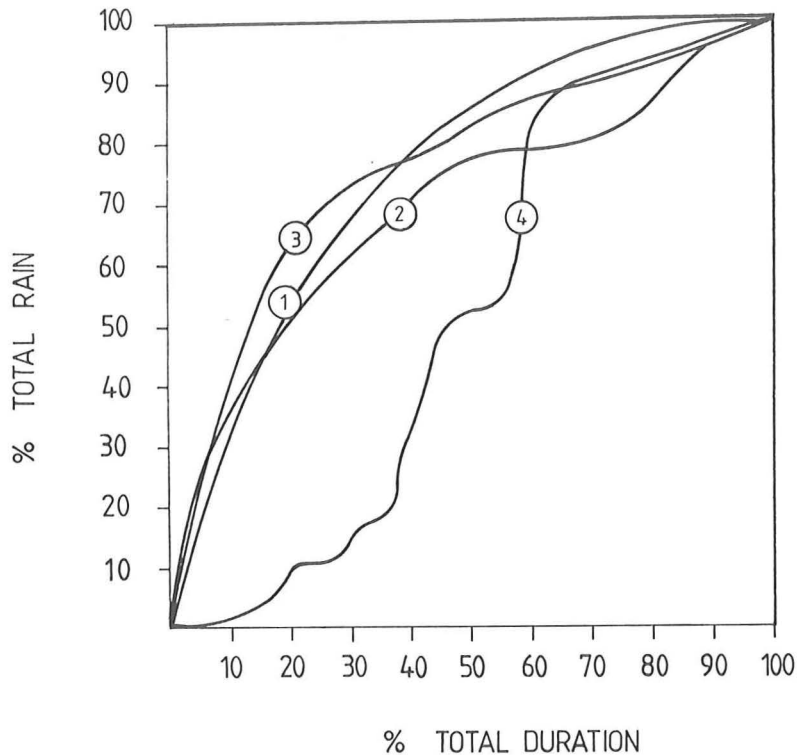


FIGURE 3.7 : SELECTED EXAMPLES OF STORM PROFILES.

1. Cloudburst at Jan Smuts : 22/12/78 - 86 mm in 1 hour.
2. Pretoria : 28/1/78 - 280 mm in 8 hours.
3. Port Elizabeth : 1/9/68 - 550 mm in 24 hours.
4. Port Elizabeth : 25-26/3/81 303 mm in 42 hours.

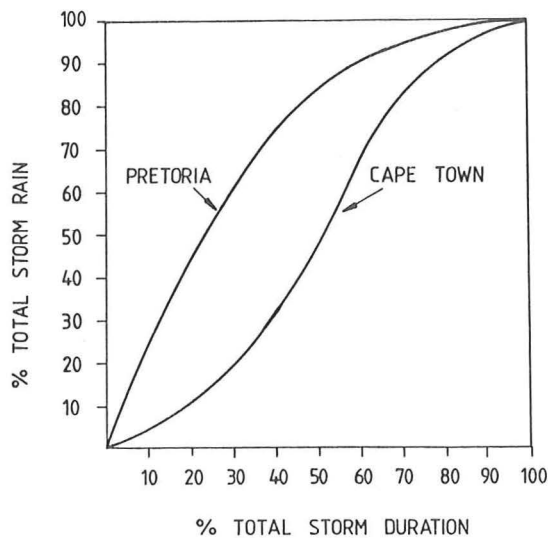


FIGURE 3.8 : CHARACTERISTIC STORM PROFILES FOR PRETORIA AND CAPE TOWN . SOURCE (16).

261 storms ranging in duration from 3 to 48 hours were studied. The resulting time distribution models were presented as probability distributions so providing measures of both interstorm variability and the general time pattern of precipitation. It was found that of total event precipitation the major proportion occurs in a relatively small part of the total event time, regardless of duration, area or the number of identifiable separate bursts of rain. Consequently, storms were classified into 4 groups depending on whether the heaviest rainfall occurred in the first, second, third or fourth quarter of storm period. For each quartile type, interstorm variability was accounted for by presenting the results as a set of percentiles as shown in Figure 3.9.



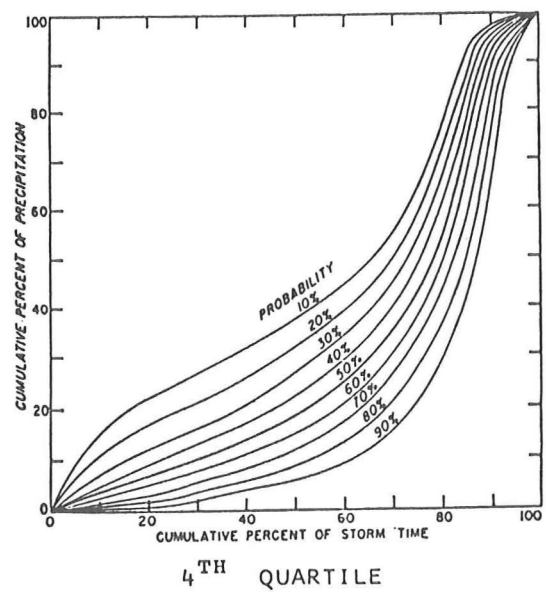
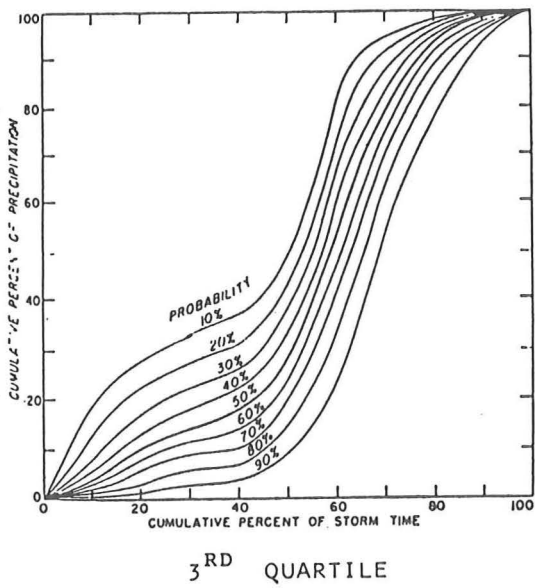
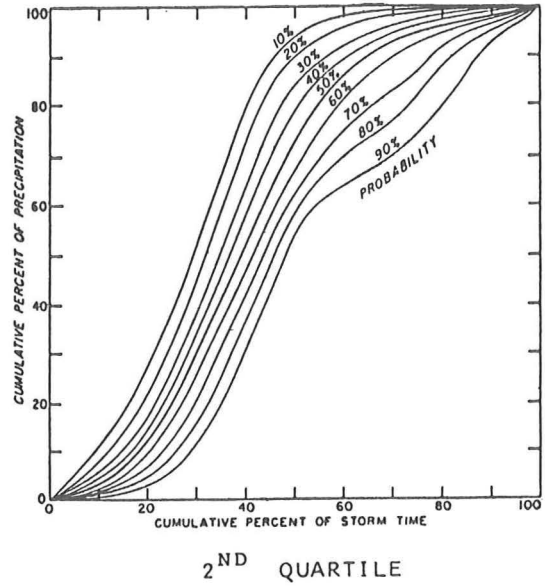
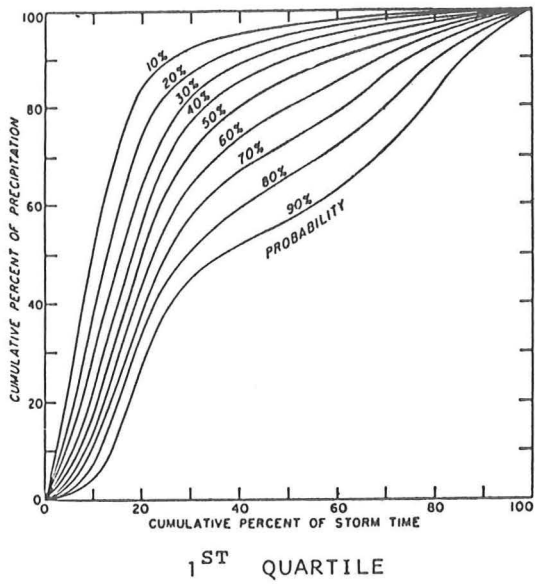


FIGURE 3.9 : PERCENTILES FOR THE TEMPORAL PATTERN OF STORM RAINFALL (AFTER HUFF, 1967).

These probability distributions allow the selection of a temporal pattern most appropriate for a particular application. In itself the median is probably the most useful statistic, although for critical drainage design the 90% percentile would probably produce the most severe surface runoff hydrograph. The percentage frequency of quartile storms analysed by Huff is shown in Table 3.1 and allows the calculation of the overall probability of any selected curve from Figure 3.9. For example, if the first quartile 10% curve is selected the overall probability of occurrence of this condition is  $.3 \times .1$  or 10% during a suitably long period, say the design life of a drainage scheme. Note that the same overall probability applies to the 90% first quartile curve if we consider the distribution as occurring for 10% or less of events.

TABLE 3.1 : PERCENTAGE FREQUENCY OF QUARTILE STORMS (AFTER HUFF (17)).

QUARTILE	FREQUENCY (%)
1	30
2	36
3	19
4	15

Huff (17) further investigated the association between quartile grouping and rain type. Table 3.2 shows that for unstable air masses, generally allied with thunderstorms, most rain occurs within the first half of the storm whilst stable air masses generally provide most precipitation in the central portion of the event.

TABLE 3.2 : PERCENTAGE DISTRIBUTION OF STORMS BY QUARTILE AND RAIN TYPE ON 400 SQ. MILES (HUFF (17))

QUARTILE	UNSTABLE AIR MASSES		STABLE AIR MASSES	
	TRW	TRW/A	TRW/RW	R
1	36,4	46,3	24,0	16,1
2	39,4	17,9	26,0	45,2
3	20,2	25,1	32,7	32,3
4	4,0	10,7	17,3	6,4

TRW = Thunderstorm; TRW/A = Thunderstorm with Hail; TRW/RW = Thunderstorm/Rainshower; R = Continuous Steady Rain.

The results obtained from the relationship between storm duration and quartile type are shown in Table 3.3.

TABLE 3.3 : PERCENTAGE DISTRIBUTION OF STORMS BY QUARTILE TYPE AND DURATION (HUFF (17)).

DURATION (HOURS)	QUARTILE			
	1	2	3	4
< 12	45	50	35	22
12 - 24	29	33	42	26
> 24	26	17	23	52

The relationships presented above may be considered representative of regions of similar rainfall climate and topography to the Mid-West of the USA. In the absence of any comparable local study it is felt that they provide a useful supplement to the analysis of critical storm drainage design for Southern Africa.

### 3.4 COMPUTATION OF STORM DEPTH FOR DURATIONS OF LESS THAN ONE DAY

In South Africa as in most areas of the world the assessment of storm depth for durations of less than one day is severely inhibited by the lack of an adequate national network of recording raingauges. Furthermore, where records are available they are generally quite short. Consequently attempts have been made to find regional relationships for the results obtained from the sparse autographic network (Adamson (3)) or to set up functional correlations such that estimates can be made at ungauged locations. Midgley and Pitman (22) and Pitman (26) followed the example of the British Flood Studies Report (24) and optimised the parameters in the expression

$$R = D \cdot R_0 / (1 + BD)^n \quad \dots\dots\dots 3.2$$

which relates the ratio of the  $D$  (hour) storm depth to that for 24 hours for the same risk and where  $R_0$ ,  $B$  and  $n$  are constants. This relationship is generally independent of return period but cannot be considered constant for the whole of South Africa and South West Africa. Since published results from autographic data are only available up to a maximum of one hour duration the optimised constants are assumed to apply to any period of less than one day.

Table 3.4 shows the computed ratios of the  $D$ (hour) duration storm depth to that for 24 hours for the summer rainfall region ( $R_1$ ) and the winter rainfall/coastal region ( $R_2$ ).

TABLE 3.4 : RATIO OF D(HOUR) STORM DEPTH TO 24 HOUR STORM DEPTH OF SAME RISK FOR SUMMER RAINFALL REGION (R<sub>1</sub>) AND WINTER RAINFALL/COASTAL REGION (R<sub>2</sub>)

D(HOURS)	R <sub>1</sub>	R <sub>2</sub>
0,1	0,17	0,14
0,25	0,32	0,23
0,50	0,46	0,32
1	0,60	0,41
2	0,72	0,53
3	0,78	0,60
4	0,82	0,67
5	0,84	0,71
6	0,87	0,75
8	0,90	0,81
10	0,92	0,85
12	0,94	0,89
18	0,98	0,96
24	1,00	1,00

The results for  $R_1$  are in agreement with those obtained by Pitman (26), no regional differences between South West Africa or the inland regions of South Africa being apparent except for the Drakensberg escarpment. However, the sample was too small for the confident estimation of a further set of ratios for this sub-region. Figure 3.10 shows the ratio of the one-hour storm rainfall to the equivalent risk one-day value and illustrates the lower values evident for the coastal/winter rainfall areas.

For storms of duration 2 hours or less Alexander (4) proposed the use of Hershfield's (13) relationships between the depth, duration and frequency of thunderstorm rainfall which have been confirmed for South African conditions by Reich (27) and Bell (5). Alexander used a linear association between mean annual maximum storm depth at a point and mean annual number of days on which thunder was recorded as independent variables and the 60 minute rainfall of 5 year recurrence interval as the dependent variable. This relationship accounted for 83% of the variance of the dependent variable ( $P_5^{60}$ ) and was thus deemed to be a suitable working scheme for estimation. Substitution of this into Hershfield's results enables the calculation of storm depth for any duration ( $t$ -minutes) and recurrence interval ( $T$ -years). The estimating equation becomes :-

$$P_T^t = 1,13(0,27 \ln T + 0,56)(0,54 t^{0,25} - 0,50)(1,55 \cdot M^{0,63} \cdot R^{0,20}) \dots\dots 3.3$$

where  $M$  is the mean annual maximum one day storm rainfall and  $R$  the mean annual number

of days on which thunder is recorded. Subsequent to this result doubt was expressed as to the accuracy of available maps of thunder records whilst  $M$  is not a readily available statistic. The recent publication of a map of mean annual lightning flash density per km<sup>2</sup> (23) and the results available in appendices A and B allowed  $M$  to be substituted by the 2-year estimated one day rainfall and  $R$  by mean annual occurrence of lightning. These variables explained 81% of the  $P_5^{60}$  storm depth and equation 3.3 may be rewritten as :-

$$P_T^t = 1,13 (0,27 \ln T + 0,56) (0,54 t^{0,25} - 0,50) (4,53 + 0,55 M_2 + 1,893 L) \dots\dots 3.4$$

where  $M_2$  is the 2 year recurrence interval one day storm depth obtained from Appendix A for South Africa and Appendix B for South West Africa, whilst  $L$  is lightning flash density obtained in Appendix E.

Table 3.5 illustrates a comparison of results from equations 3.3 and 3.4 and the ratios to 24 hour data for given  $T$  from Table 3.4. Two points are immediately apparent. Firstly Hershfield's relationship does not hold for durations in excess of 2 hours as is seen from the estimate of  $P_5^{60}$  for Pretoria from both equations 3.3 and 3.4. Most other estimates using these relationships for similar durations are above that for 24 hours at the same return interval. The second point is the relative overestimation of storm depth if  $R_1$  is used incorrectly for coastal/winter rainfall regions (cf. result for Port Elizabeth).

Thus for the computation of storm risk for durations of 2-hours or less the ratios  $R_1$  or  $R_2$  in addition to equation 3.4 may be used. For longer storm periods equation 3.4 is no longer valid.

TABLE 3.5 : COMPARATIVE ESTIMATES OF STORM RAINFALL FOR DURATION OF LESS THAN 24 HOURS USING DAILY DATA

STATION	$T$ (YEARS)	$\Delta t$ (HOURS)	EQUATION 3.4	ALEXANDER Eqn. 3.3	RATIO TABLE 3.4
Willowmore	20	1,00	45	31	58
Pretoria	50	6,00	166*	162*	140
Pretoria	20	0,25	43	42	42
Nelspruit	5	0,50	50	46	40
Durban	100	0,50	97	80	88 (127)
Port Elizabeth	50	3,00	107	99	109 (140)
Cape Town	20	1,00	44	34	36 (52)
Cape Town	20	6,00	81	62	65 (74)
De Aar	50	6,00	98*	86*	75
Windhoek	50	8,00	143*	142*	80
Windhoek	20	1,00	60	60	41
Johannesburg	20	0,25	41	40	37
Johannesburg	50	6,00	158*	155*	121
Kokstad	100	0,50	72	63	66
Kuruman	20	1,00	64	55	67
Carolina	10	1,00	69	52	50
Lydenburg	50	6,00	131*	122*	88
Pietersburg	20	2,00	84	72	81
Bloemfontein	20	0,50	47	55	47
Swellendam	50	2,00	91	-	86 (117)
Knysna	50	0,25	40	-	40 (52)

\* Computed value for  $\Delta t$ (hours) in excess of 24 hour storm depth for same  $T$ .

( ) Computed value for 'inland'/summer rainfall region ratio ( $R_I$ )

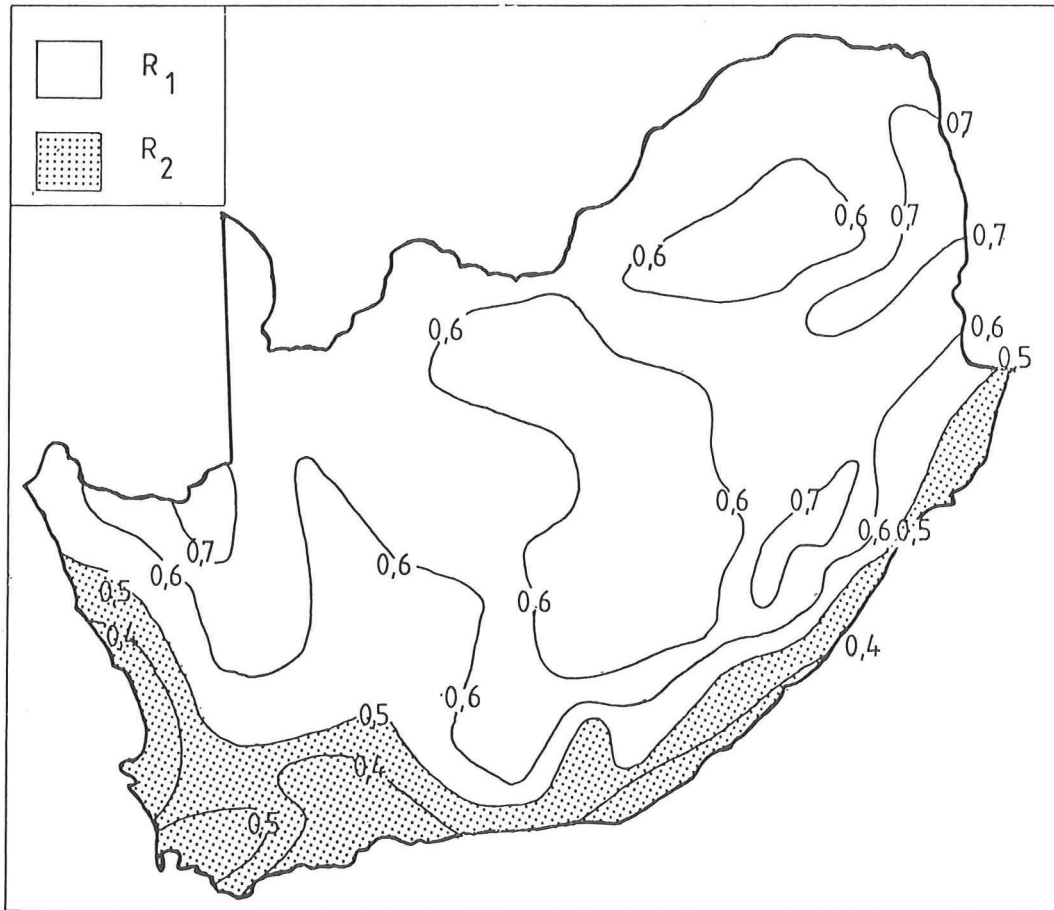


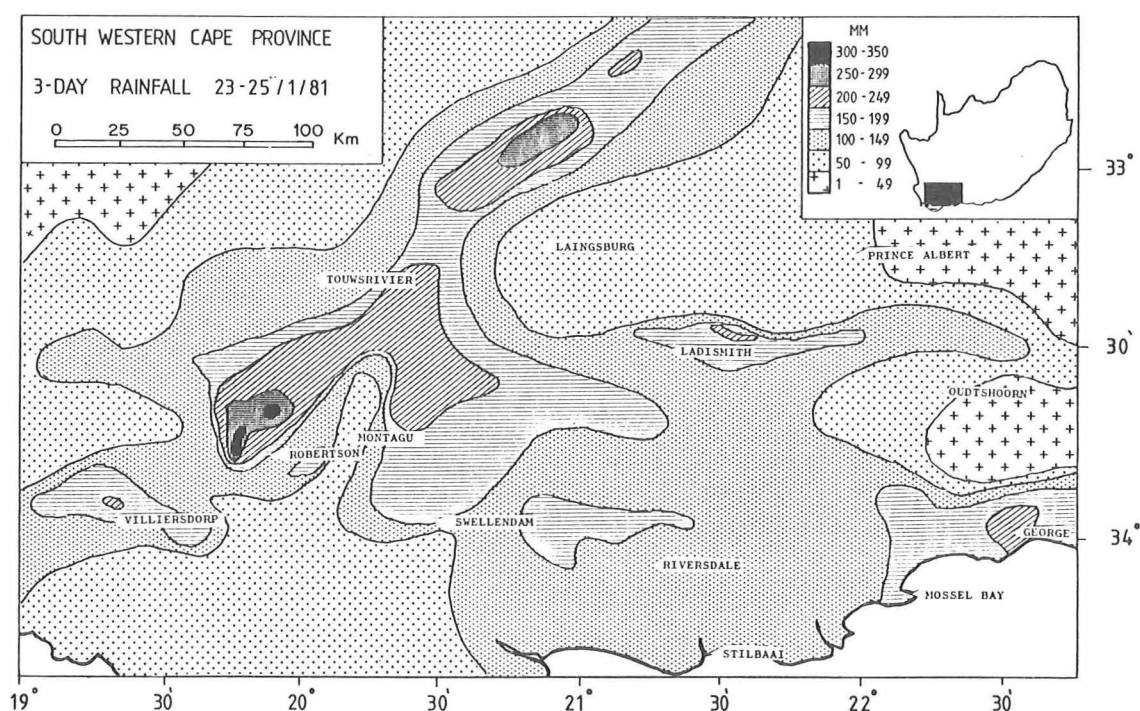
FIGURE 3.10 : ISOLINES OF THE RATIO OF THE 60 MINUTE TO ONE DAY STORM RAINFALL FROM DATA PUBLISHED IN (3) AND REGIONS OF APPLICATION OF THE GENERALIZED RATIOS R1 AND R2 (TABLE 3.4) FOR ANY DURATION LESS THAN 24 HOURS.

## PART IV

### SOME HISTORIC EXTREME STORM EVENTS OVER SOUTHERN AFRICA

The following short accounts of a number of extreme storm events over Southern Africa are intended to illustrate patterns of rainfall for various durations and areas that resulted in loss of life, massive damage to property, crops and livestock and disrupted communications. The risk of such events at any point in the subcontinent may be small but their occurrence within the total subcontinental space has been historically quite frequent.

#### 4.1 THE LAINGSBURG FLOOD DISASTER 25TH JANUARY, 1981



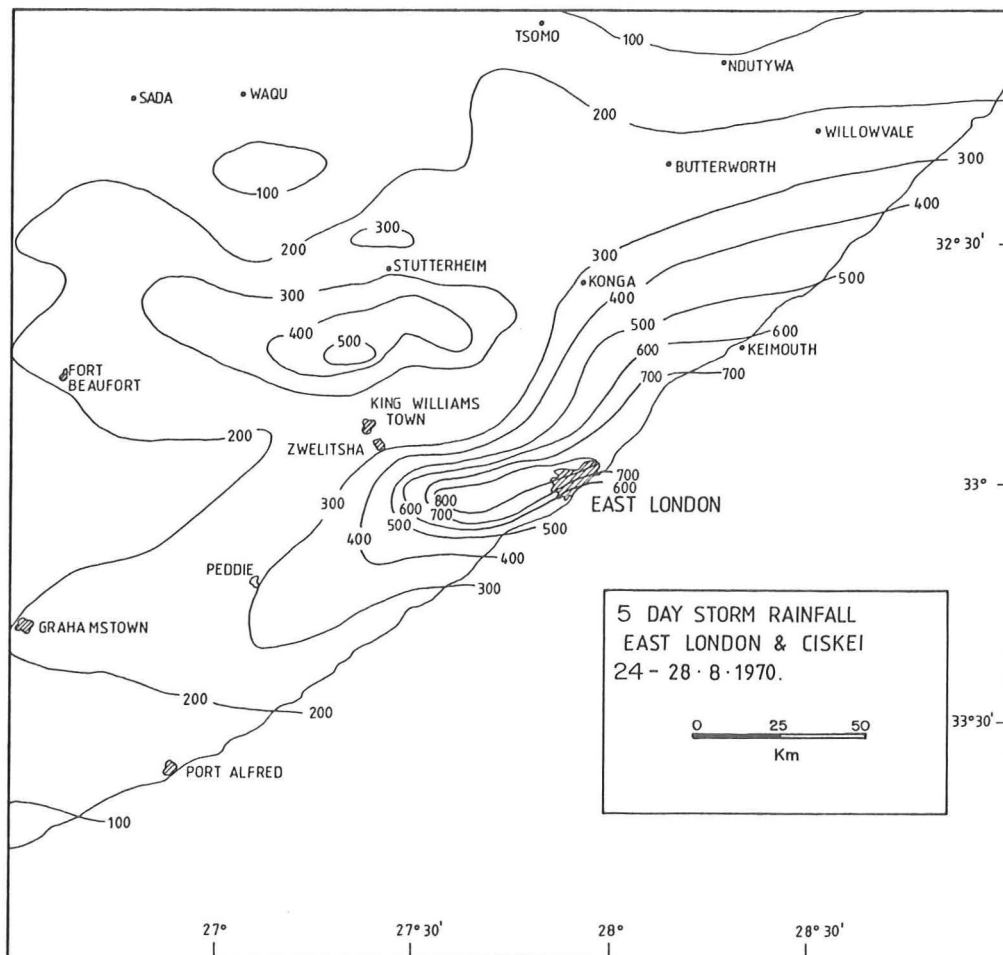
The Laingsburg flood disaster of January 1981 has been described as South Africa's greatest natural catastrophe (Estié (10)). The three day storm, although never providing particularly intense rainfall did provide such a volume to cause a floodpeak estimated at 5 700 cubic metres per second in the Buffels River. These floodwaters washed away a considerable part of the town of Laingsburg with the loss of 104 lives. The synoptic situation which gave rise to the storm is certainly not uncommon along the coastal regions of the Eastern Cape, Transkei and Natal where many exceptional storms can be accredited to such a system. However, the location and movement of the low pressure cell so far inland to cause the disaster was certainly atypical. The causative synoptic situation is colloquially known as a "Black South-Easter" in which a strong high pressure system to the south of the continent feeds moist, warm-air into a low pressure system over the southern parts of the country. During the 24th January an



upper air low broke off from its source region south of the continent to form a cut-off low (10) which moved further into the interior along the periphery of a ridge of high pressure. The pressure gradient between the two was very steep which encouraged a stream of warm, moist air to be directed into the low which further intensified. By the 25th January the low reach its maximum level of development in terms of atmospheric vertical motion and vorticity thus favouring considerable rainfall. The maximum rainfall recorded on the 25th was to the north and north west of Laingsburg where up to 160 mm fell. Along the coast most rain had occurred on the previous day with 122 mm recorded at George for example. Figure 4.1 shows the isohyets for the combined rainfall days of 23rd, 24th and 25th January and illustrates that although the rainfall pattern over the three days was largely determined by the position of the cut-off low, topographic influences did play a part (10).

The risk at any point in the Karoo regions of a 24 hour rainfall in excess of 100 mm is very low indeed, being in excess of once in one hundred years. However, the spatial probability of such events anywhere in the region as a whole is far greater.

#### 4.2 THE EAST LONDON STORM 24th to 28th AUGUST, 1970



A "Black South-Easter" situation, which is typically confined to the coastal regions caused unprecedented heavy rains over East London and the Eastern Cape during August 1970. Typically the synoptic situation consisted of :-

- (a) An intense anticyclone south of the Cape following the passage of a cold front,
- (b) a surface low pressure system over the southern and eastern interior, and
- (c) a cold cut-off upper air low over the southern and central interior.

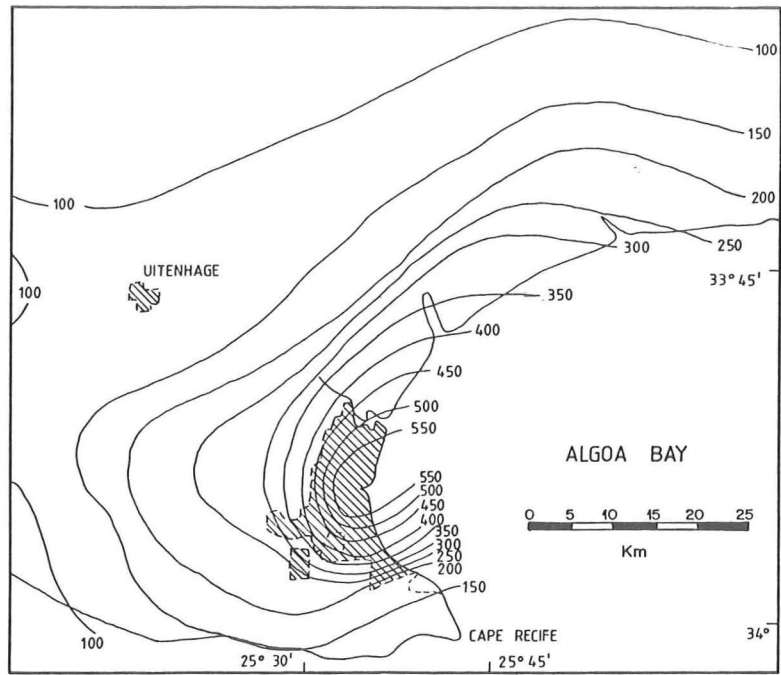
This pressure distribution results in an onshore circulation in the lower atmosphere which experiences topographic uplift as the air moves inland. Additionally this circulation is inclined to feed in warm, moist and potentially unstable Indian Ocean air from the east (Hayward and van den Berg (12)). The heaviest rainfalls occurred over East London where the most marked frontal contrast between the warm moist Indian Ocean air and cooler air with lower dewpoints flowing from the south west existed. The relatively long duration of the exceptional rains was caused by the very slow eastward movement of the entire system. During the 5-day period a total of 855 mm (equivalent to the mean annual rainfall) was recorded at East London airport, of which 447 mm was recorded during the 24 hour period ending at 08h00 on the 28th. On the 27th rainfall rates averaged 50 mm/hour in the morning and reached a maximum of 70 mm/hour.

"Black South-Easter" conditions or synoptic situations of greater similarity have been responsible for most of the exceptional downpours on the east coast of South Africa. Examples of such events are 360 mm on the 1st of January, 1932 at Wagenboomskraal in the Outeniqua mountains, 265 mm on the 21st of October, 1953 at East London, 459 mm on the 17th of May, 1959 near Port Shepstone and 552 mm on the 1st of September, 1968 at Port Elizabeth. The figure of 590 mm at Eshowe, Zululand on the 5th of May, 1940 remains the record one-day maximum fall for South Africa.

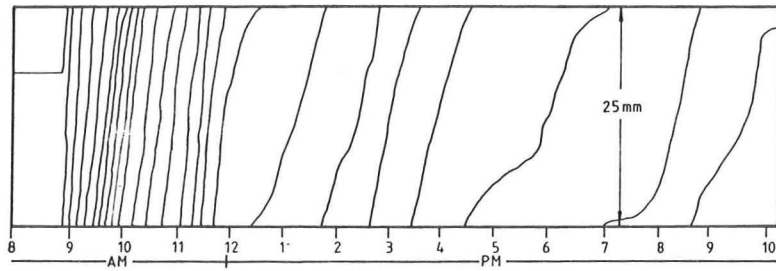
#### 4.3 THE PORT ELIZABETH STORM OF 1ST SEPTEMBER, 1968

(See Figure 4.3)

Precisely the same synoptic conditions as those described above contributed to the outstanding storm event over Port Elizabeth during September, 1968 when up to 470 mm of rain was recorded over 4 hours and over 550 mm during 24 hours. Maximum rainfall intensities varied from 20 - 30 mm in 15 minutes and resulted in floodwaters over 25 mm deep over the airport runway. Initial estimates of damage were in the region of R30 million (11). The intensity and rainfall volume associated with the storm cannot be totally explained by cyclonic circulation on the synoptic scale and other incidental factors such as topography and uncommon local instability must be considered as contributory elements (11). Similar conditions were repeated in March 1981 to produce serious flooding and damage. (Figure 4.4)

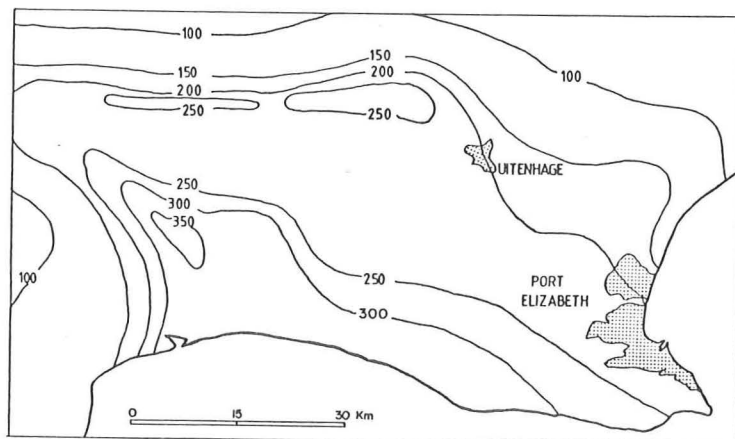


1 DAY RAINFALL. PORT ELIZABETH. 1/9/68



1/9/68  
 AUTOGRAPHIC RECORDER. FAIRVIEW RESERVOIR. P. ELIZABETH.

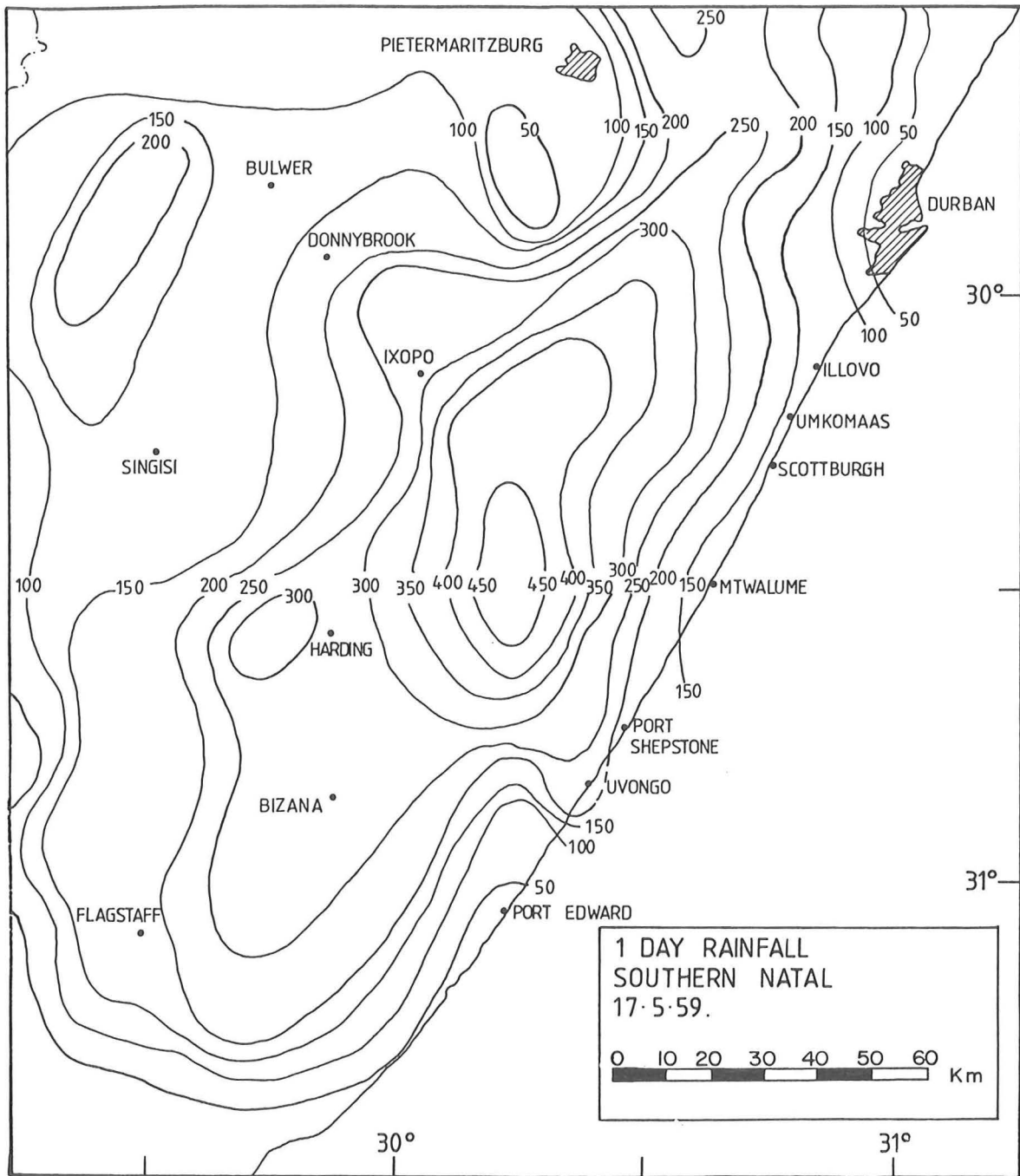
FIGURE 4.3



PORT ELIZABETH & GAMTOOS VALLEY. 26/3/81

FIGURE 4.4

4.4 THE NATAL SOUTH-COAST STORM OF MAY, 1959



A cold front advancing up the coast accounted for the heaviest storm rainfalls recorded over southern Natal since records began. An associated depression to the south-east of the front ultimately extended as far north as Zululand and the Eastern Transvaal and intensified during the 16th of May drawing cold moist air from behind the front to the south west and warm moist air from the east and north (20). These opposing airstreams were present to a height exceeding 6 000 metres and temperature differences between opposing air masses reached 12 C. The cyclonic circulation resulted in strong on-shore movements of warm maritime air from the south-east which rising above the cold front and influenced by topographic effects rose and cooled rapidly. During the 16th up to 230 mm of rain fell further south over the Bashee River catchment between East London and Umtata, whilst on the 17th 495 mm was recorded inland of Port Shepstone in the Umzimkulu River catchment. Over 4 200 km<sup>2</sup> received falls in excess of 300 mm during the 24 hours of the 17th. Maximum recorded intensities at the height of the storm reach 35mm/hour.

Damage caused by the ensuing floods, in addition to the loss of 49 lives, was largely to bridges. Due to the incised nature and steepness of coastal catchments there is little surface storage and floodpeaks are consequently relatively high and flood waves very fast moving.

#### 4.5 THE DURBAN STORMS OF 29TH AND 30TH DECEMBER, 1977

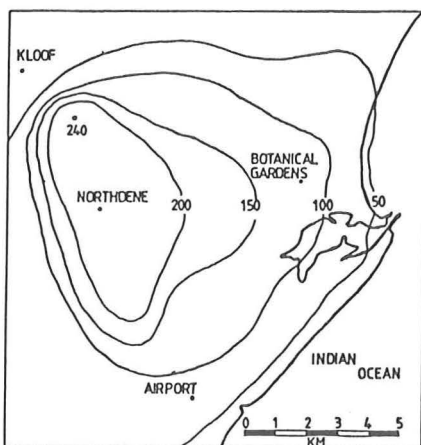


FIGURE 4.6(A) : 29/12/1977

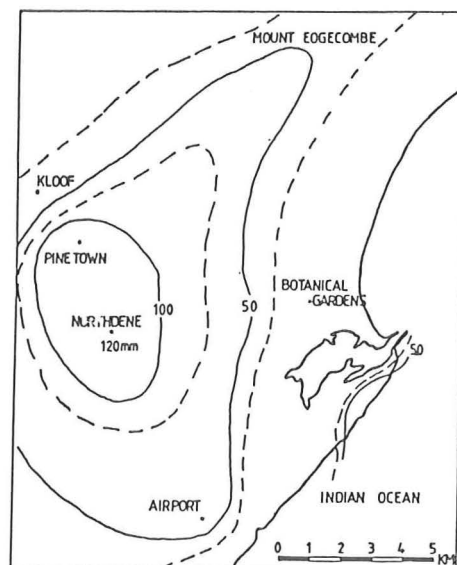


FIGURE 4.6(B) : 30/12/1977

Although they represent two separate and distinct events the Durban thunderstorms of 29th and 30th December, 1977 are noteworthy for their unusually high rainfall in a short period, and the fact that the storms occurred two nights in succession over an identical area. Furthermore the generating mechanism remained stationary over the 48 hour period (de Villiers (8)). A coastal low was situated off Natal and maritime air fed in over the southern interior from a ridge of the South Atlantic high. A cut-off low developed over the southern Cape and resulted in a north-westerly airflow and berg wind conditions over the coast. The temperature difference between this air and that behind the coastal low resulted in a marked line of convergence and temperature discontinuity and consequent increase in potential instability. The stationarity of the coastal low for 48 hours maintained the conditions whilst the localised nature of the two events indicates that topography played an important role.

The maximum recorded rainfall for the 29th was 240 mm in 3 hours and for the 30th 120 mm in 2 hours, both storms occurring in the late evening. Indications are that prolonged periods of up to 80 mm/hour were quite likely (8). A similar convergence zone situated over southern and central Natal earlier in the same year produced 94 mm in one hour and 158 mm in 2½ hours at Durban airport.

#### 4.6 FLOOD RAINS IN THE EASTERN CAPE 19TH TO 22ND AUGUST, 1971

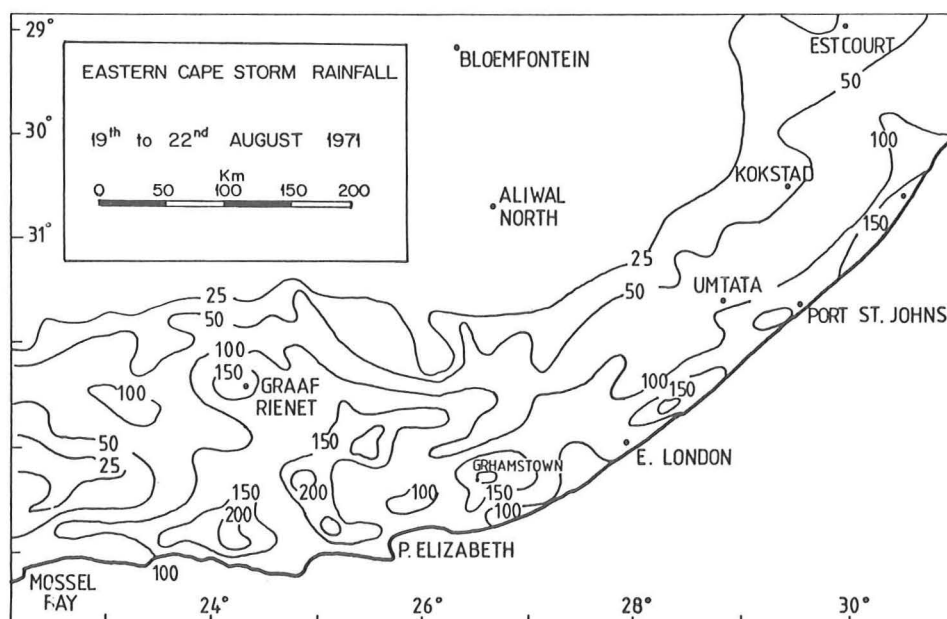


FIGURE 4.7

A cut-off upper air low associated with "Black South-Easter" conditions contributed to extensive storm rainfalls over the Eastern Cape during 1971. This storm was unusually extensive with up to 196 mm recorded for the total storm period and over 40 000 km<sup>2</sup> receiving more than 100 mm of rainfall. Snowfalls and gale force winds up to 140 km/h were also recorded. At Grahamstown the downpour was the highest recorded since 1880 (Keyworth (19)) and in all 83 people were drowned or died of exposure.

The synoptic situation began with the passage of a cold front along the coast and a

rapidly deepening depression over the southern interior. A strong convergence zone developed over the south-eastern regions of the country causing exceptional precipitation. The interior low although slowly moving to the north-east split into two and a cut-off low developed in the upper air causing intense pressure gradients inland from the coast from Mossel Bay to Port Shepstone. This accounted for the rapid influx of maritime air associated with gales as well as for the large area affected by the storm.

4.7 THE PRETORIA STORMS OF 1955, 1959 AND 1978

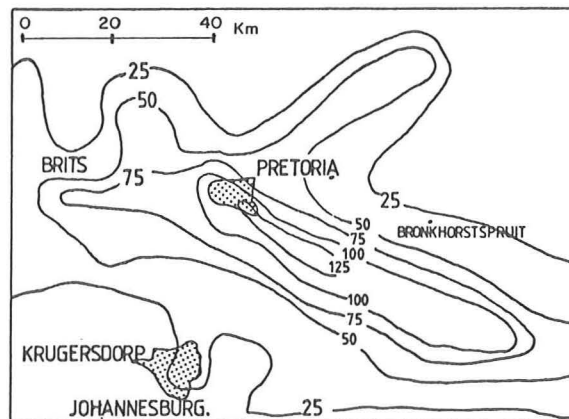
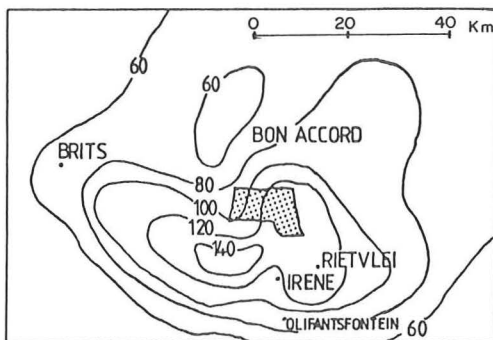
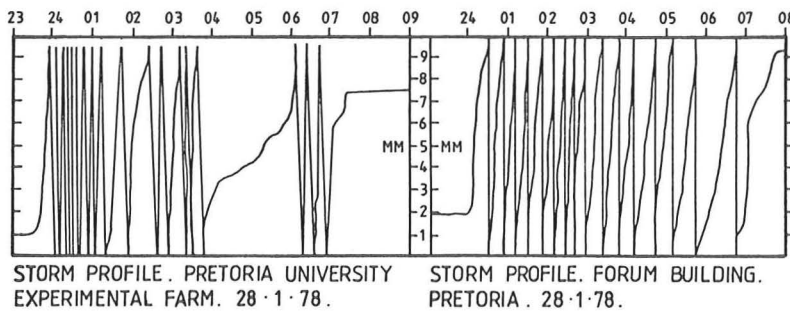
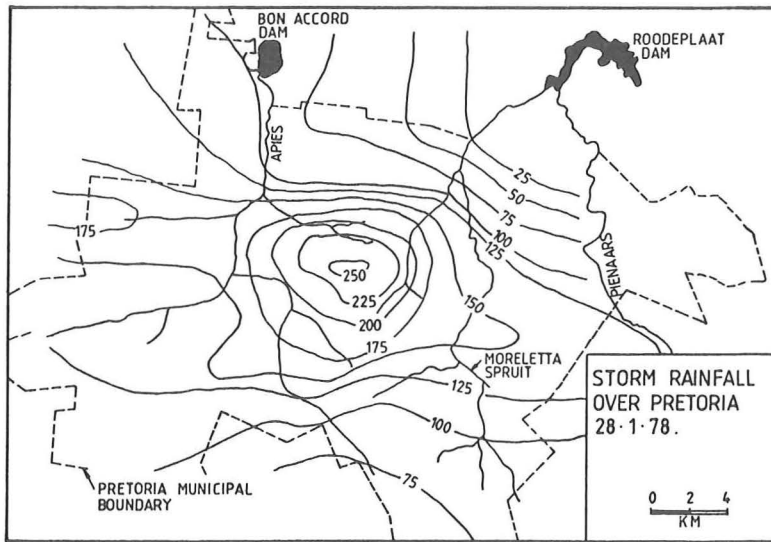


FIGURE 4.8 : STORM RAINFALL PATTERNS OVER THE PRETORIA REGION.

Exceptional storm rainfalls over Pretoria on 21/11/55, 25/1/59 and 28/1/78 show remarkable similarities in terms of synoptic situation and the influence of topography. Table 4.1 shows the maximum point rainfalls recorded in addition to that for the event of 27/12/39 for which although no synoptic data are available it is suspected that the weather generating conditions were much the same.

TABLE 4.1 :

DATE	MAX. POINT RAINFALL	PLACE	DURATION	MAX. INTENSITY
27/12/39	164 mm	Burgers Park	-	-
21/11/55	135 mm	Swartkops	24 hours	70 mm in 1 hour
25/01/59	175 mm	Waterkloof	48 hours	-
28/01/78	280 mm	Rietondale	8 hours	60 mm in 1 hour

Figure 4.8 shows the isohyetal patterns of the storms which are analogous in their east-west orientation. The common synoptic feature of the three storms is a trough of low-pressure over the greater part of the northern interior with air to the north being warm and moist whilst to the south the air is cooler and drier, circulating around the ridge of the South Atlantic high. (Esti  (9)). The coalescence of these two air masses causes a temperature and dew-point discontinuity and conditions ripe for frontal thunderstorm activity. In themselves such conditions are typical for the summer months over the Highveld region. However, the storms over Pretoria are notable in their stationarity, duration and intensity as well as for their areal extent which local topographic features provide the most likely explanation (9). Along an east-west axis the terrain in the area rises over 300 metres fairly rapidly and the positioning of a temperature/dew point discontinuity over the northern edge of the Witwatersrand would enhance uplift effects and sustain storm development for a considerably longer period than would be normal in flatter areas (9).

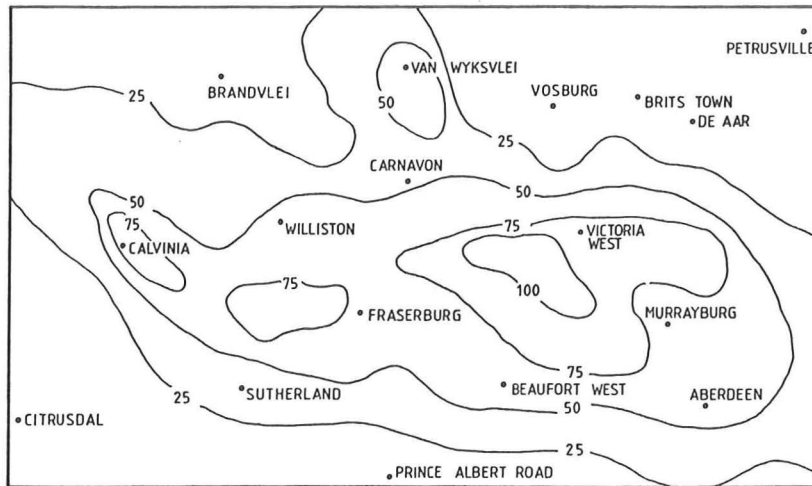
#### 4.8 FLOOD RAINS IN THE KAROO 26TH AND 27TH MARCH, 1961

(See Figure 4.9)

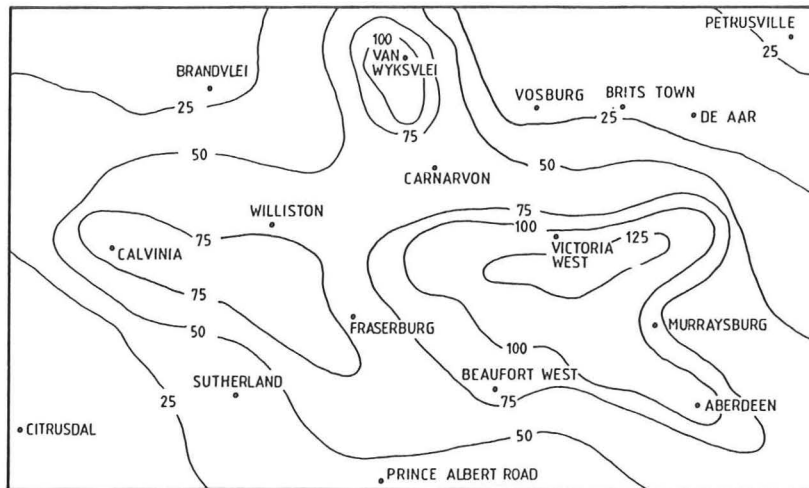
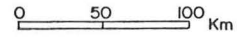
Occasionally exceptional rainfalls occur from a synoptic situation with which heavy falls are not normally associated. Such was the case during March 1961 over an area of 39 000 km<sup>2</sup> of the central Karoo. Widespread heavy rains in the region usually occur with appreciable cyclonic development at the surface (Triegaardt (30)), but during the course of these notable rains the shallow trough of low pressure that did exist filled almost completely. It seems that the very good correlation between topography and rainfall provides the key factor to the whole development and remarkable similarities exist with the weather situations which accounted for the Pretoria storms described above. In this case a deep layer of very humid air moving northwards was forced to ascend the ridge of higher ground extending from Sutherland eastwards where altitudinal differences of 800 metres are quite common. This triggered and sustained a line of thunderstorms moving over the higher ground from west to east. Time



FIGURE 4.9



1 DAY RAINFALL. KAROO REGION 26/3/61.



2 DAY RAINFALL. KAROO REGION 26 + 27/3/61.

profiles of the storm (30) illustrate initial intensities to less than 30 mm/hour but these soon dropped to 10 mm/hour for 80% of total storm duration which was generally in the region of 14 hours.

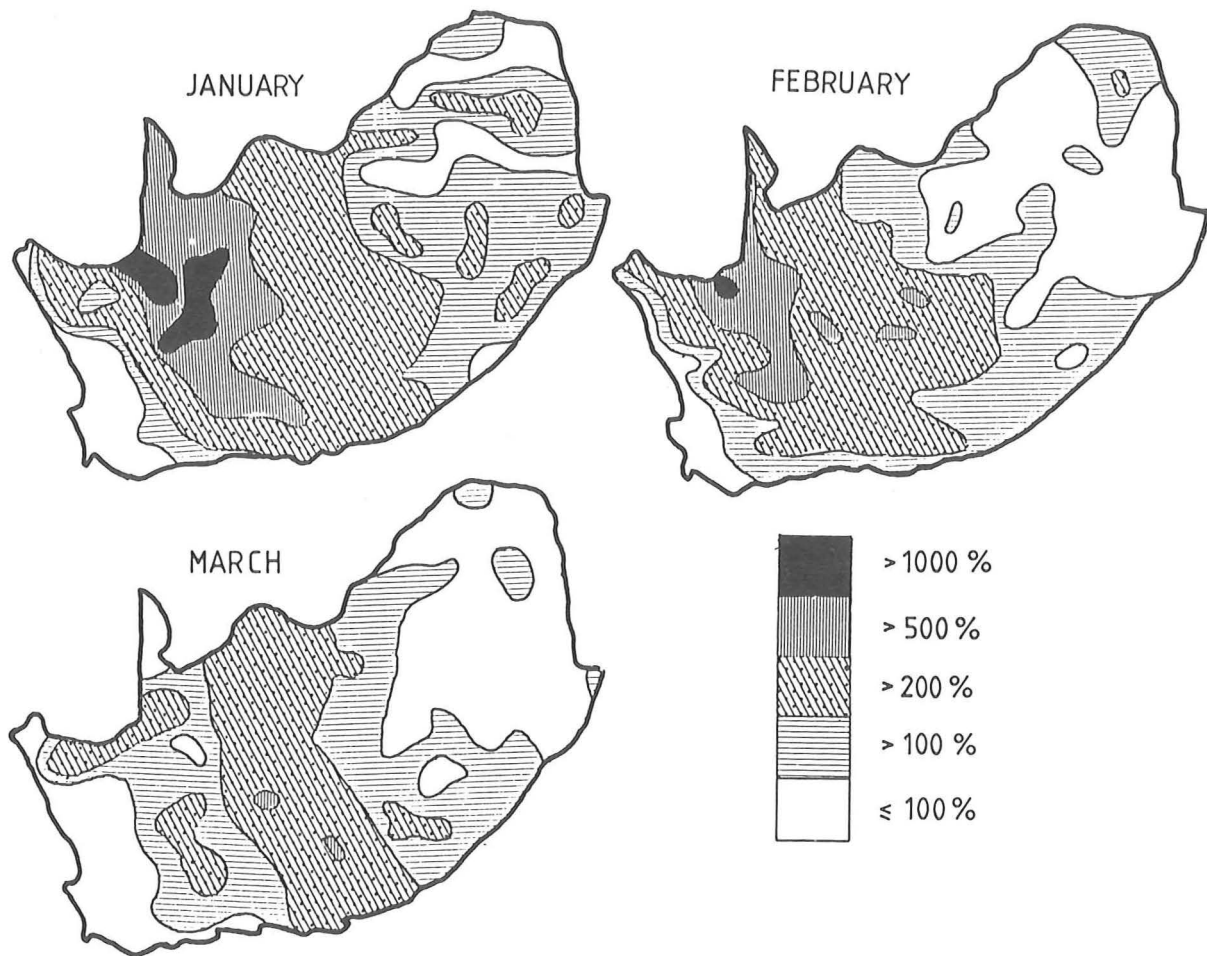


FIGURE 4.10 : PERCENTAGE MEAN MONTHLY RAINFALLS DURING THE ANOMALOUS CLIMATE REGIME OF JANUARY TO MARCH 1974. SOURCE (29).

The anomalous climate and weather systems over the central Republic from January to March, 1974 culminated in the serious flood rainfalls over the Great Fish and lower Orange catchments during the first three days of March, 1974. This climate anomaly has recently been studied in detail by Taljaard (29) who ascribes the three months of exceptional rains to above normal pressures to the south of the continent and negative departures of pressure over the western and northern parts of the interior plateau. This resulted in an increase in the northerly component of the atmospheric circulation and the encouragement of trough formations over the central parts of the subcontinent. Such conditions are favourable for widespread rainfall over these regions and Figure 4.10 illustrates that monthly rainfalls over 1 000 % of average were recorded whilst 500% of the average monthly rainfall was a common feature. These unprecedented conditions were repeated from November 1975 through to April 1976 and are ascribed to the same anomalous circulation.

The heavy rains from January 1974 onwards had a disastrous effect on the agricultural economy of the central regions of South Africa. Reports of serious flooding began to appear from mid-January and during the first four days of February Mariental and Keetmanshoop in South West Africa received 129 mm and 103 mm respectively or 60% of normal mean annual precipitation.

Devastating floods occurred on the 6th and 7th of February along the Natal Coast, and in the sugar growing areas around Stanger 60 people lost their lives. Crops rotted along the lower Orange River and flood warnings were issued along the Vaal River below Bloemhof. By the end of February Bushmanland and the Western Karoo were extensively flooded and from the 28th persistent intense rains over the south-western Free State, northern Cape and Eastern Province caused serious flooding in the Great Fish, Sundays and upper Orange Rivers. The runoff from this 100-200 mm of rainfall (Figure 4.11) caused a flood peak to sweep down the Orange, consequent massive damage to irrigation schemes and a record water level at Upington. Over the regions affected by this 3 month period of exceptional rainfall total damage was estimated to be R100 million (29).

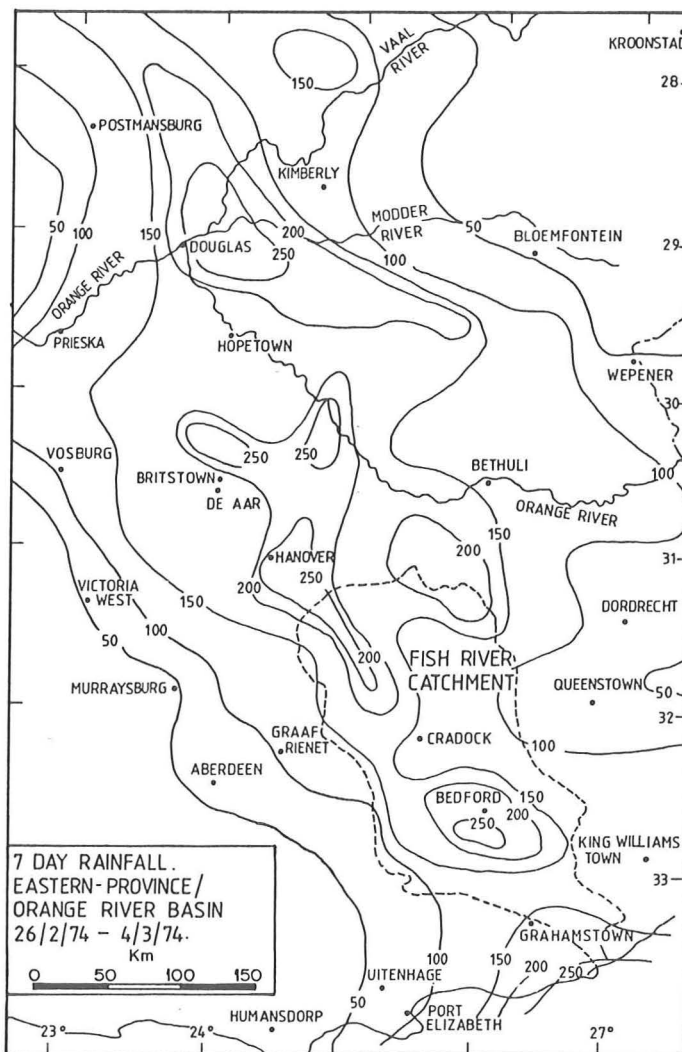
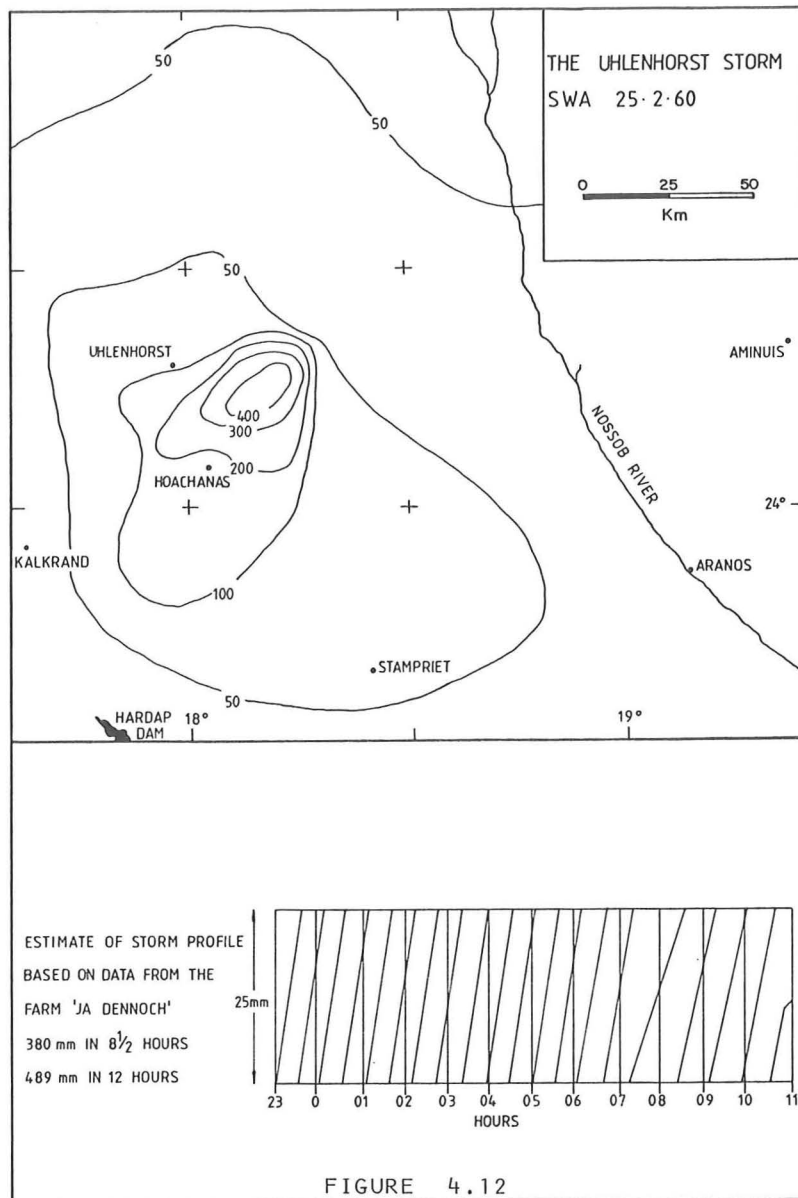


FIGURE 4.11

4.10 THE UHLENHORST CLOUDBURST SOUTH WEST AFRICA 25TH FEBRUARY 1960



The Uhlenhorst cloudburst of February 1960 represents the highest point rainfall recorded in South West Africa since European settlement. Approximately 365 km<sup>2</sup> situated in an area with a mean annual rainfall of 250 mm received an average precipitation of 230 mm within 12 hours, whilst 45 km<sup>2</sup> received in excess of 400 mm. Maximum recorded point rainfall was 489 mm, the mean intensity in the earlier part of the storm being 45 mm/hour. Data on the temporal properties of the storm (28) are shown in Table 4.2.

TABLE 4.2 : TIME PROFILE OF THE UHLENHORST CLOUDBURST AT THE FARM JA DENNOCH

TIME	DATE	DURATION	RAINFALL
23h00	24/2/60	0 hours	0 mm
07h30	25/2/60	8½ hours	380 mm
11h00	25/2/60	12 hours	489 mm

The likely cause of the storm was intense local and well developed convectional instability. The most interesting hydrological facet associated with the event was that it occurred in dune country which is devoid of a normal surface water drainage system. This caused temporary lakes and surface storage of considerable depth and the consequent evaporation and supply to groundwater was substantial. The overland flow that did occur in the embryonic tributaries of the Auob was very slow with velocities in the region of 1 metre/second.

FUTURE RESEARCH NEEDS AND CONCLUSION5.1 INTRODUCTION

The major thrust of the present study has been to provide tabulated estimates of  $n$ -day storm risk for the greater part of South Africa and South West Africa/Namibia. It is felt that this data base of some 2 500 rainfall stations gives the most comprehensive basis for design storm determination currently available within the region. The need for regional functional approximations derived from short records and limited data is made unnecessary by the volume of data and spatial coverage achieved in the study. However, only  $n$ -day rainfall depths were available on such a scale which leaves an obvious gap in the report in that no results are presented for short duration storm risk. Empirical relationships have been presented for the computation of such estimates until such time as recording raingauge data are available for analysis. Even when these data are studied there will still be a need to relate short duration storm depths to daily data since the coverage of recording raingauges within South Africa is too thin for confident regionalization.

Material on the spatial and temporal properties of storms has been included in the report because of its relevance to design. Most of it is, however, derived from studies of overseas results since these aspects of storm rainfall have received very little attention within Southern Africa. The applicability of American and European results to the sub-continent is not proven but in the absence of comparable local studies, with the exception of some University of the Witwatersrand reports (21, 22, 26, 33), it is felt they provide a useful addition to the present work and illustrate the gaps in the knowledge of storm rainfall and the direction in which research could be pursued.

The following suggestions for rainfall data storage and retrieval, for research into storm rainfall for design purposes and for research into the meteorological aspects of storms and Southern African rainfall in general largely reflect problems, thoughts and ideas experienced during the execution of the present work.

5.2 DATA REQUIREMENTS

Presently approximately 8 000 daily rainfall records are available on computer magnetic tape for South Africa and South West Africa/Namibia. Although such a mass of data provides an excellent library for information retrieval it is, in its present form far too large for efficient data handling in a study of any aspect of rainfall on the sub-continental scale. A coverage of 2 000 stations on a grid pattern would, it is felt, provide a suitable data base for such studies. The remaining 6 000 stations could be used to fill-in the gaps in the primary data and perhaps extend them to fixed record lengths. Gaps in the data at the moment preclude any meaningful analysis of real time daily rainfalls necessary for example in the study of drought periods or runs of wet and dry sequences. Work on providing this primary data base has already begun for the purposes of spatial statistical studies of Southern African rainfall deficiencies.

The break-point digitising of recording raingauge charts is already well in progress. Although the majority of these records, relative to the daily data are rather short they will provide the means for the computation of meaningful relationships between daily and hourly extreme storm rainfalls and allow the considerable refinement of the empirical functional equations and ratios presented herein. Such data are further required for studies of the temporal properties of storms.

A further requirement in the study of extreme storms is the association of rainfall and synoptic situation. Not only would a study of such data improve forecasting and flood warning procedures but would add considerably to the knowledge of the synoptic climatology of Southern Africa. Storms could be classified according to their origin in terms of closed tropical migratory systems, local convection and frontal systems and the rainfall extremes due to them analysed as separate data sets. In this way some insight could be gained in the frequency of extremes and their relationship with storm type.

Most regions of South Africa are amply covered by daily rainfall data whilst for South West Africa data are lacking for the coastal regions, eastern border and the Caprivi. The biggest and most important data gap in the region is Lesotho where hardly any data are available. Since this part of the Drakensberg is the source region of the Orange River with its large dam storages it is of considerable relevance that some insight into the rainfall régime of the area be achieved. Correlations with topography are impossible for such a mountainous region since data are also poor in the adjacent areas of South Africa. For Southern Botswana many rainfall studies of the northern Cape Province are appropriate whilst for the central regions South West African/Namibian results could be extrapolated into the area. However, it would be useful to study the accuracy of such assumptions with the analysis of some data from Botswana.

### 5.3 RESEARCH REQUIREMENTS FOR CIVIL ENGINEERING DESIGN

As has already been pointed out the most important omission from the present study are results for storm risk of durations of less than one day. For small catchment hydrology and the design of urban drainage systems storms of six hours and less are critical. Once the digitized recording raingauge data are generally available a frequency analysis of extremes for various durations should be pursued along the lines of the present study of  $n$ -day data. The partial duration series approach is suggested for two reasons :

1. Because the periods of record are rather short it will maximise the information content relative to the use of annual maxima, and
2. for small catchments and urban storm studies rainfall depths with a recurrence interval of 5 years or less are of great importance. The partial duration series approach is rather more accurate at this end of the of the frequency domain (2).

Once these frequencies have been tabulated a workable relationship between them and the one-day storm depth needs to be established such that estimates can confidently be made

throughout the sub-continent. Bell's ratios as discussed in Part III provide the starting point for such a study but only for durations of 2 hours and less. For durations of 2 hours and more the refinement of the ratios  $R_1$  and  $R_2$  as presented in Table 3.4 could be achieved given that these are derived from results at only 62 sites (3). The additional frequency analyses will enable much more confidence to be placed in the ratios and in any broad regionalization possible from the results. The values of  $R_1$  and  $R_2$  in Table 3.4 are presently being compared with those derived from a study of 100 Australian stations and a selection from various regions of the United States.

Once the above ends have been achieved the frequency domain of analysis for design storm determination is more or less complete. The only possible addition would be to analyse the seasonal or monthly distribution of extreme rainfalls and their associated frequency. Obviously storm rainfall is more likely in some months than in others and it would be useful to attach probabilities to such events on a seasonal basis. Such results would, for example be useful in the design of temporary river works during the construction of hydraulic structures and in the assessment of the likelihood of storm damage to crops at critical growth stages. Such a study would readily lend itself to regionalisation with a series of graphs showing isolines of storm risk at various annual recurrence intervals plotted against the months of the year.

The temporal and areal properties of storm rainfall in Southern Africa have received very little attention with the exception of a few rather limited analyses. Studies of the areal reduction of point storm depths have, for example, been restricted to the Pretoria region (32) and to large regional  $n$ -day events (33). What is required is a library of maps of the isohyetal patterns of historical storms such as those presented in Part IV. Urban areas generally provide a sufficient density of non-recording gauges for maps of small area, high intensity storms to be drawn. Additionally at least one recording gauge is generally present for the precise duration of the storm to be established. The density of non-recording gauges for  $n$ -day events covering large areas is such that the isohyets can also be drawn. From this storm map library some insight into the areal properties of rainfall events could be achieved and perhaps refined by further consideration of synoptic storm type. The data could be supplemented by results from well instrumented research catchments such as those near Bethlehem in the Orange Free State. Overseas areal reduction curves such as those proposed by Nicks and Igo (25) could be confirmed or denied for Southern African application and a set of curves recommended for standard design practise.

Many of the emergent rainfall-runoff models coming into use for routine hydrological analyses are no longer restricted by the assumption of spatially uniform rainfall depth as is the case with linear unit hydrograph theory. Consequently, the position and movement of storm centres can be accommodated and their effects on flood peak and volume estimated. Obviously the output of many catchment systems is sensitive to these areal aspects of storm development and movement. Additionally, in many areas storms follow a dominant track as a consequence of topographic features, for example. For the study of such aspects of storm rainfall radar studies are being applied although preliminary research is required to develop new or extend existing techniques for the statistical and climatological analysis of vast quantities of radar data (24).



The work of Huff (17) gives ideal guidelines for the study of the temporal characteristics of storm rainfall. In looking at the distribution and variance of storm profiles and relating them to synoptic type Huff has moved away from the somewhat impractical concept of "the typical storm". For small catchments and urban drainage problems in particular the temporal properties of the input hyetograph can be critical and can be accommodated in a number of the more refined mathematical models. In this way the sensitivity of small catchment systems to the properties of the storm profile can be investigated.

Finally, for design storm purposes all research into storm rainfall should be tailored to the needs of flood prediction and assessment. Although design hydrology is secured to the concept of recurrence interval the amount of information conveyed by this expression of risk is minimal. For example, research is needed into such questions as: "What is the distribution of the event magnitude for a given recurrence interval?" or "What is the distribution of the recurrence interval for a given event magnitude?". In this way the risk that an event is greater than any recurrence interval can be found and the expectation of encountering such an event during the design life of a project be estimated. Some thoughts along these lines are presented in (2).

#### 5.4 RESEARCH REQUIREMENTS FOR GENERAL HYDROLOGICAL STUDIES

Many of the research requirements in design storm determination are of relevance to meteorological studies and the understanding of rainfall processes. Hydrologists are more concerned with modelling the statistical and probabilistic structure of rainfall whilst meteorologists are more concerned with research into rainfall as a space-time physical process. Recently the emergence of physically based statistical hydrology has seen the fusion of the two approaches, although the mathematical developments in the field have been far too complex for little more than theoretical assessments of their merit. It is in this arena, however, that most potential lies for the modelling of rainfall on the catchment, regional and subcontinental scale.

A primary requirement in Southern Africa is an atlas of rainfall-depth probabilities on a monthly basis. This would be of practical use to hydrologists, agriculturalists and climatologists and if a model or series of models can be found then for any station/month the exceedence probability of any rainfall can be computed using the fitted model parameters. Such a research programme is currently in its development stages and will ultimately allow the objective identification of rainfall regions for the study of rainfall deficiencies.

Although the stochastic and deterministic modelling of streamflows is well developed the statistical modelling of the rainfall input is rather crude. In fact in most applications uniform depth over the catchment is assumed which combined with averaging between gauged points greatly reduces the variance of model input. There is a need therefore to review the structure of the input to rainfall-runoff models and account for its space-time characteristics. Many models already exist for the structure of rainfall time series and a few more complex representations of their spatial relationships. A large field of research therefore lies in unifying the space-time properties of rainfall with those of streamflow.

Such stochastic models of sequences provide the tools for a thorough hydrometeorological study of Southern African rainfalls. Attention should be directed at the distribution of annual precipitations, the distribution of wet season lengths and precipitation volumes, the expected frequency and variance of dry and wet period runs and the spatial-statistical properties of rainfall surfaces, for example.

Finally, there are many areas of the subcontinent where rainfall data are sparse for streamflow modelling purposes. The efficient modelling of rainfall will enable the regional transfer of model parameters to areas where data are lacking.

#### 5.5 CONCLUSION

It is intended that the present study of  $n$ -day storm rainfall depths in South Africa and South West Afric/Namibia when supplemented by an analysis of recording raingauge data, will become part of a comprehensive design package for floods and storm precipitation. Companion volumes will include guidelines and recommended procedures for such analyses. It is hoped that the presented study has contributed towards this goal.

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APPENDIX A

TABULATED N-DAY STORM RISK : SOUTH AFRICA

APPENDIX B

TABULATED N-DAY STORM RISK SOUTH WEST AFRICA/  
NAMIBIA

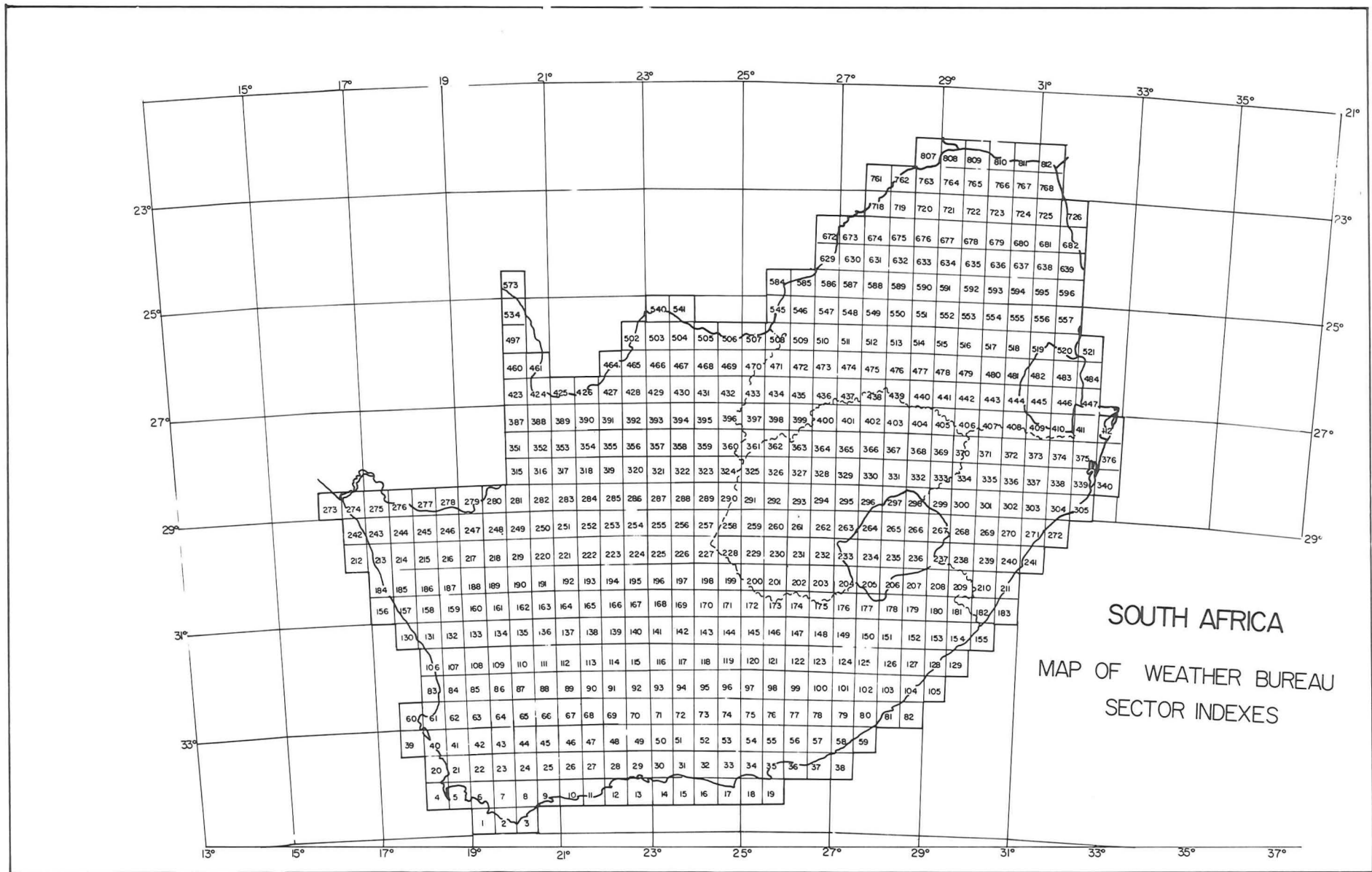




APPENDIX C1

MAP OF WEATHER BUREAU RAINFALL SECTOR INDICES :  
SOUTH AFRICA



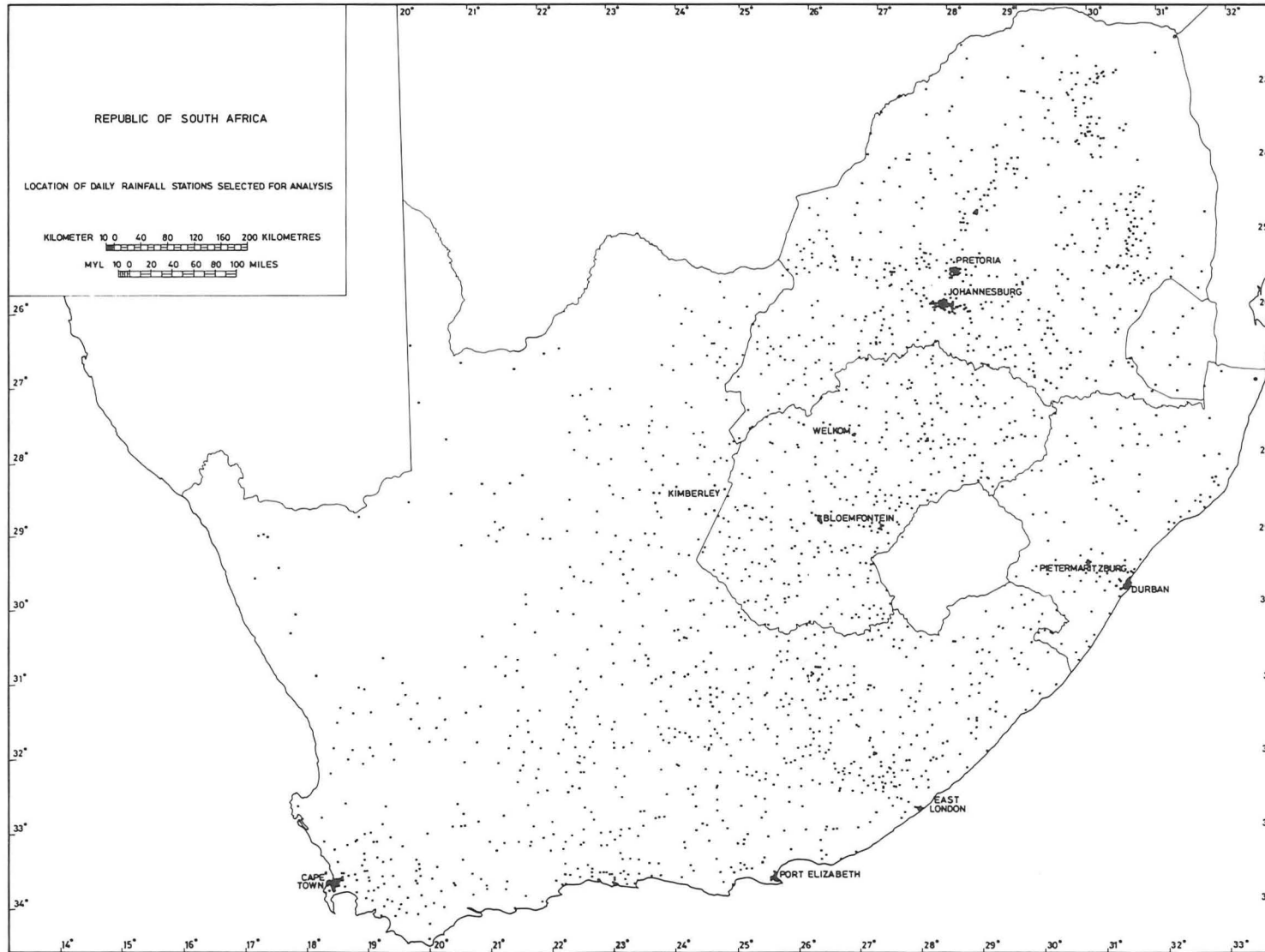




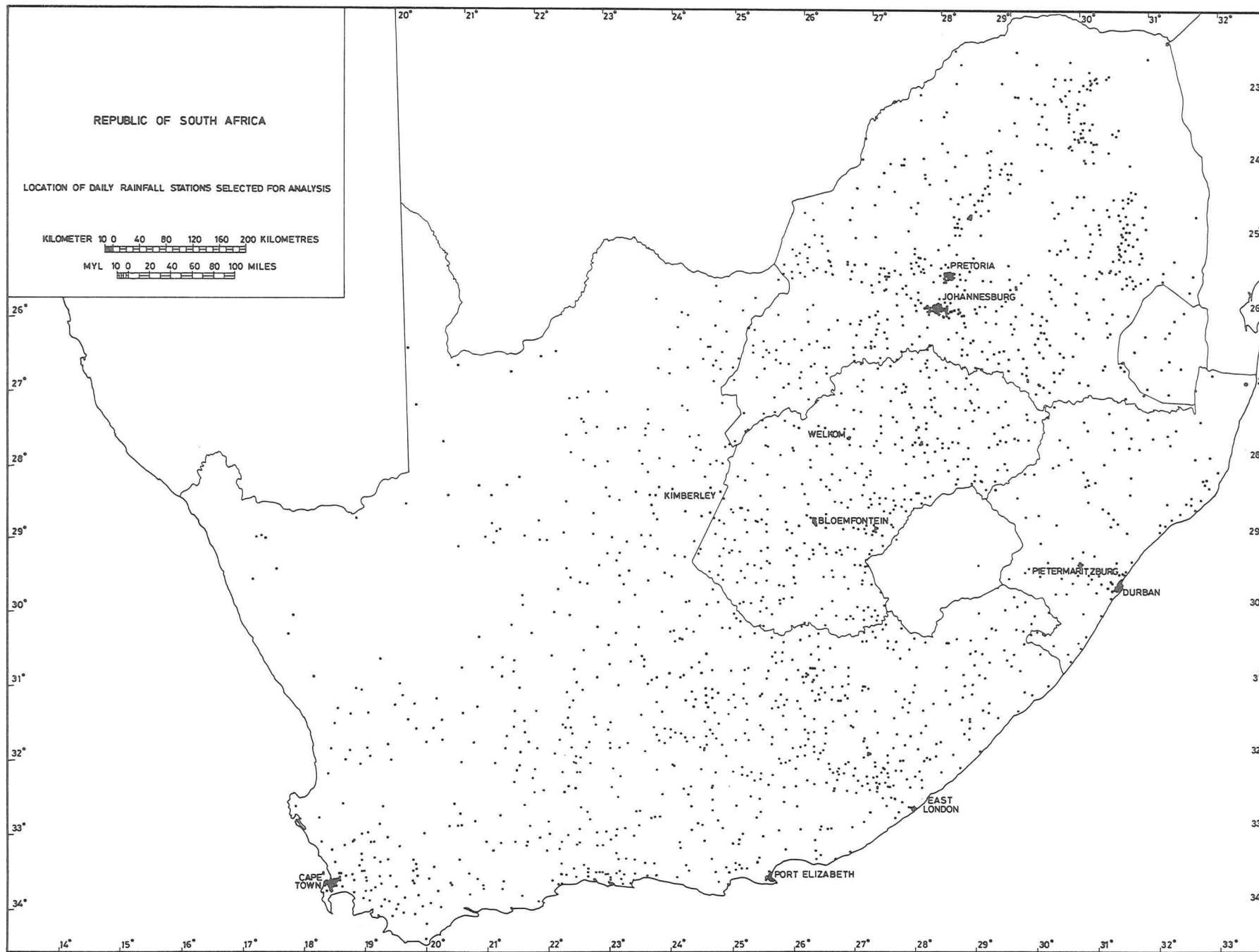
APPENDIX C2

MAP OF STATIONS ANALYSED FOR N-DAY STORM RISK :  
SOUTH AFRICA





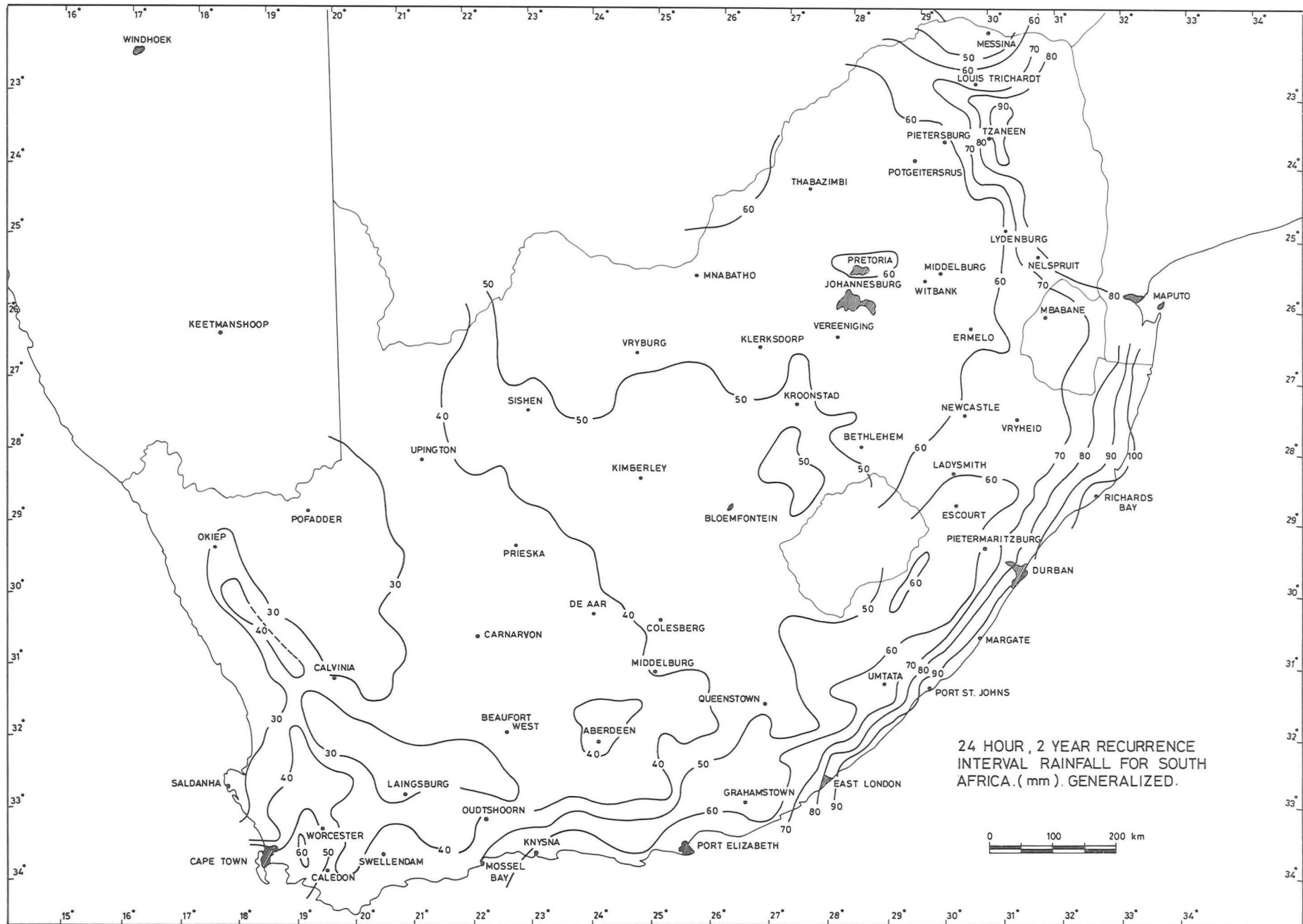




APPENDIX C3.1

MAP OF 2-YEAR RECURRENCE INTERVAL STORM RAINFALL :  
SOUTH AFRICA





24 HOUR, 2 YEAR RECURRENCE INTERVAL RAINFALL FOR SOUTH AFRICA. ( mm ). GENERALIZED.

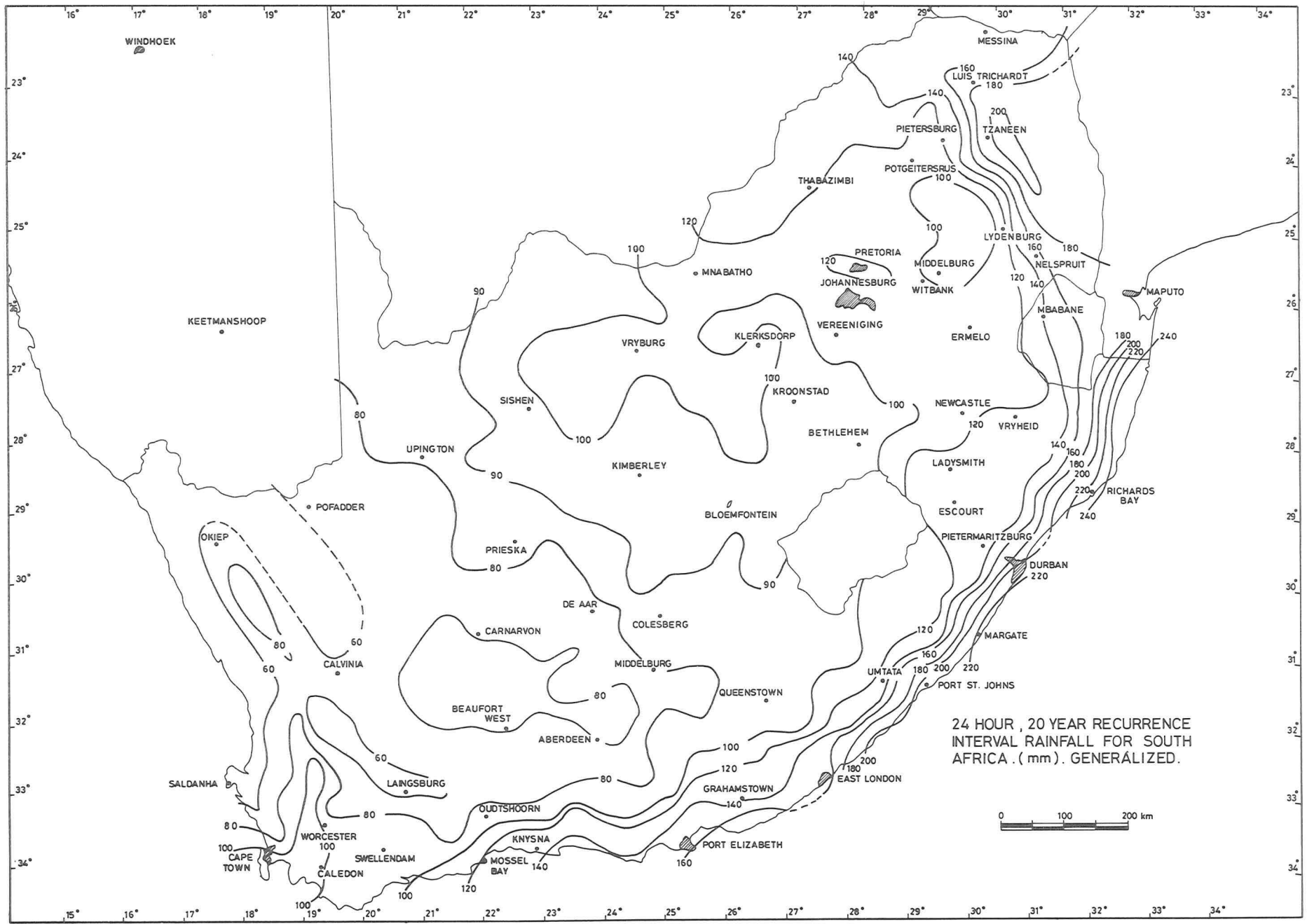




APPENDIX C3.2

MAP OF 20-YEAR RECURRENCE INTERVAL STORM  
RAINFALL : SOUTH AFRICA





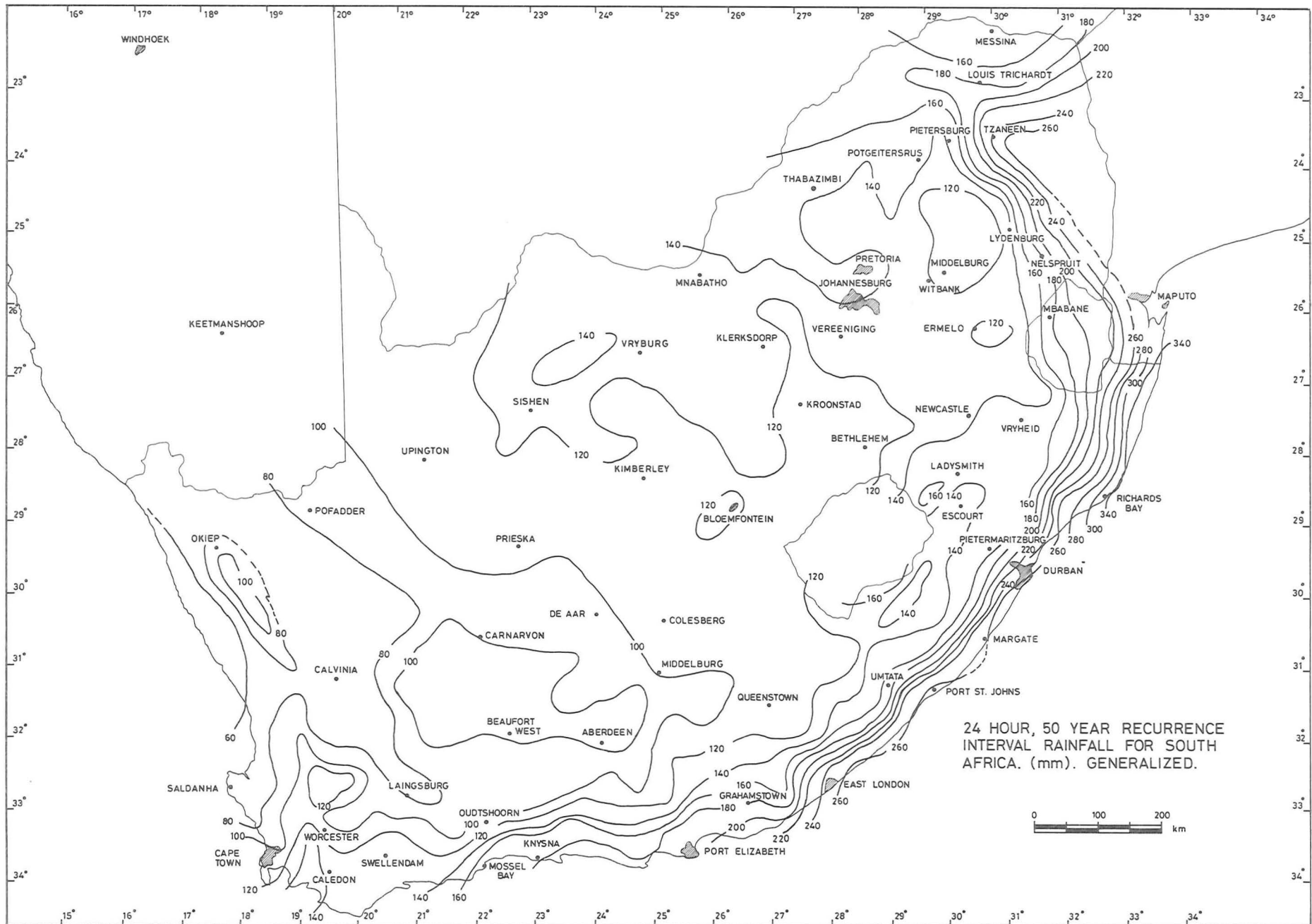




APPENDIX C3.3

MAP OF 50-YEAR RECURRENCE INTERVAL STORM  
RAINFALL : SOUTH AFRICA



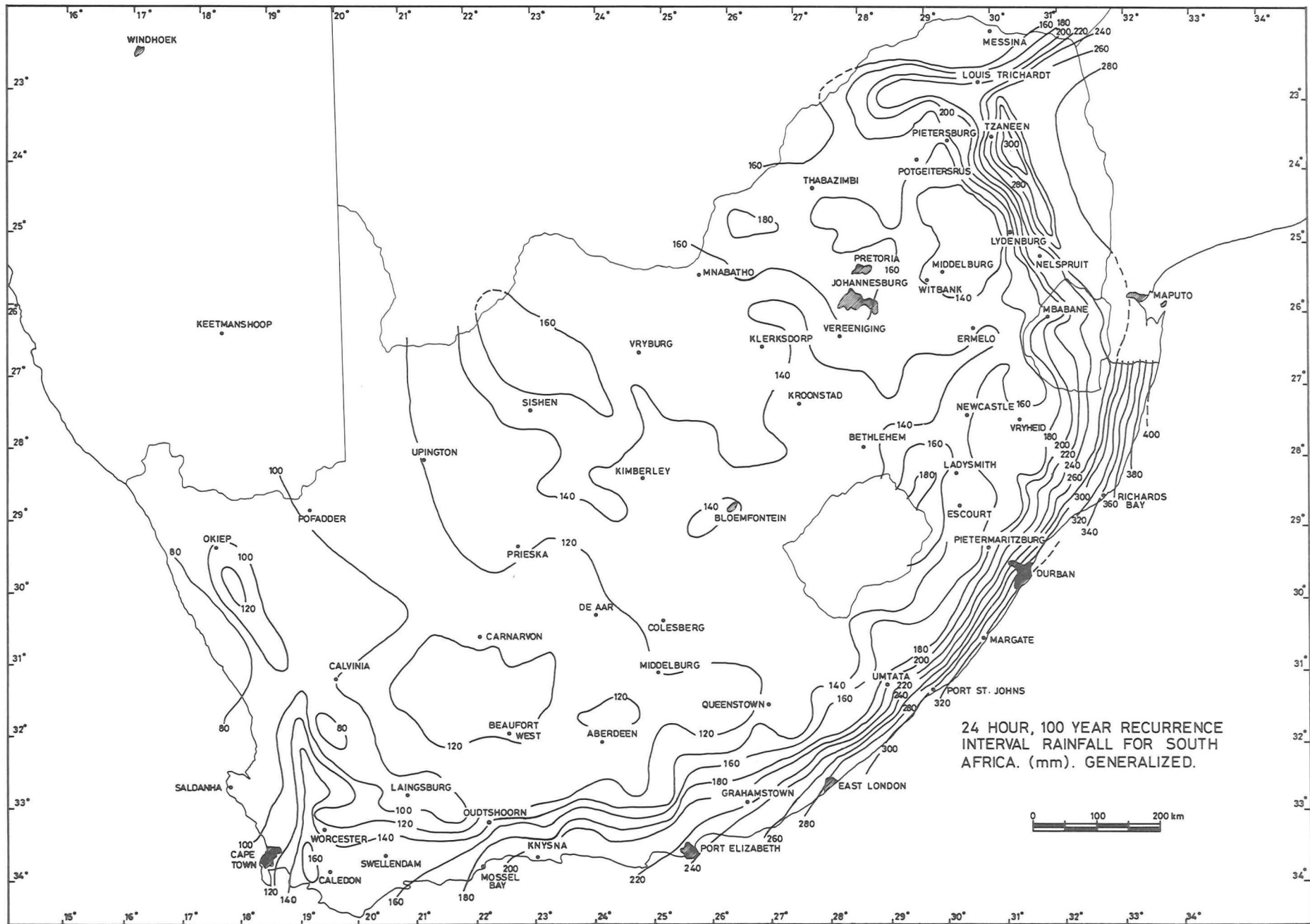




APPENDIX C3.4

MAP OF 100-YEAR RECURRENCE INTERVAL STORM  
RAINFALL : SOUTH AFRICA









APPENDIX D1

MAP OF WEATHER BUREAU RAINFALL SECTOR INDICES :  
SOUTH WEST AFRICA



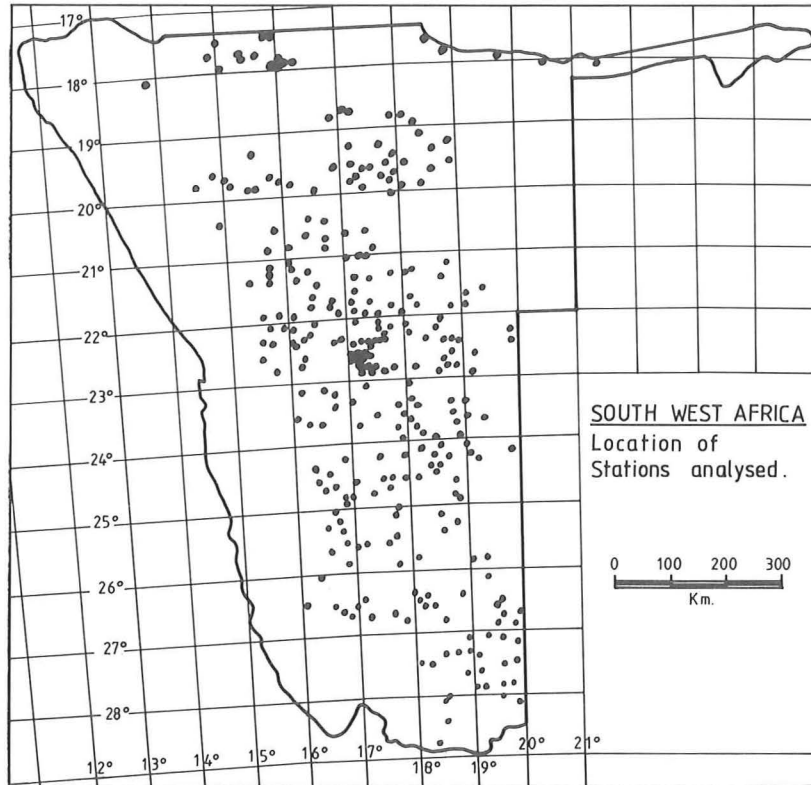




APPENDIX D2

MAP OF STATIONS ANALYSED FOR N-DAY STORM RISK :  
SOUTH WEST AFRICA







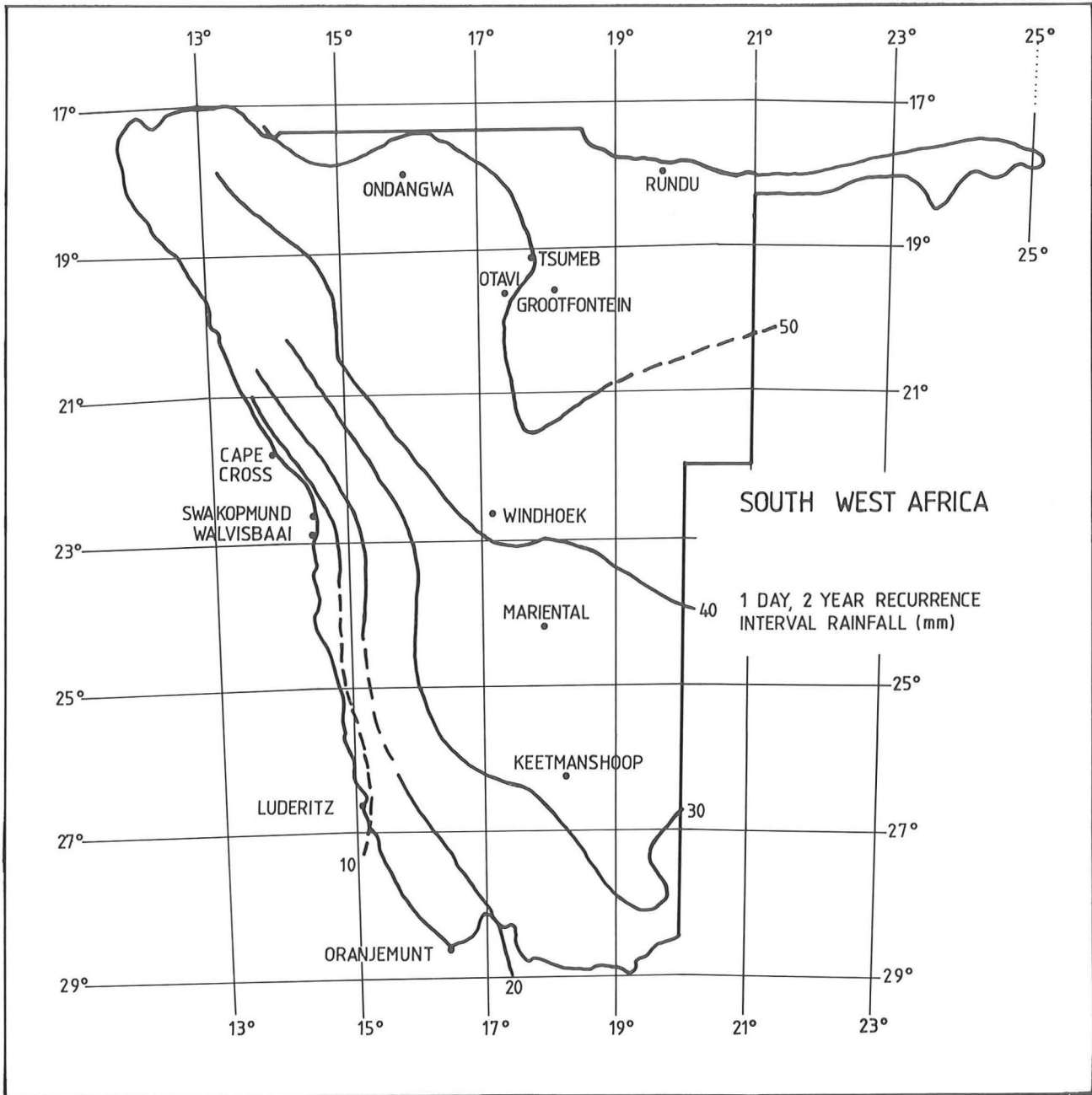


APPENDIX D3.1

MAP OF 2-YEAR RECURRENCE INTERVAL STORM RAINFALL :  
SOUTH WEST AFRICA



Appendix D3.1.

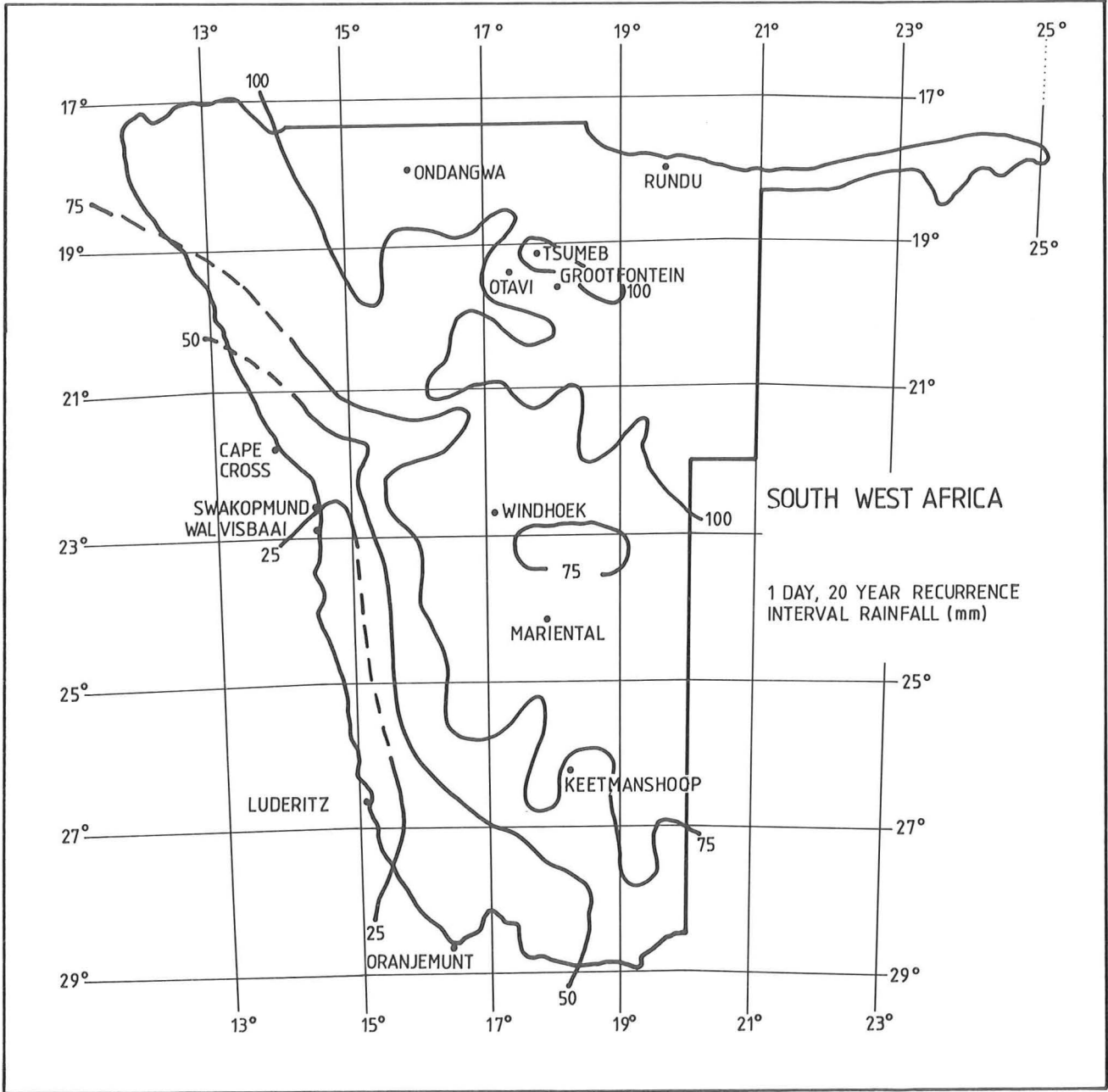




APPENDIX D3.2

MAP OF 20-YEAR RECURRENCE INTERVAL STORM RAINFALL :  
SOUTH WEST AFRICA





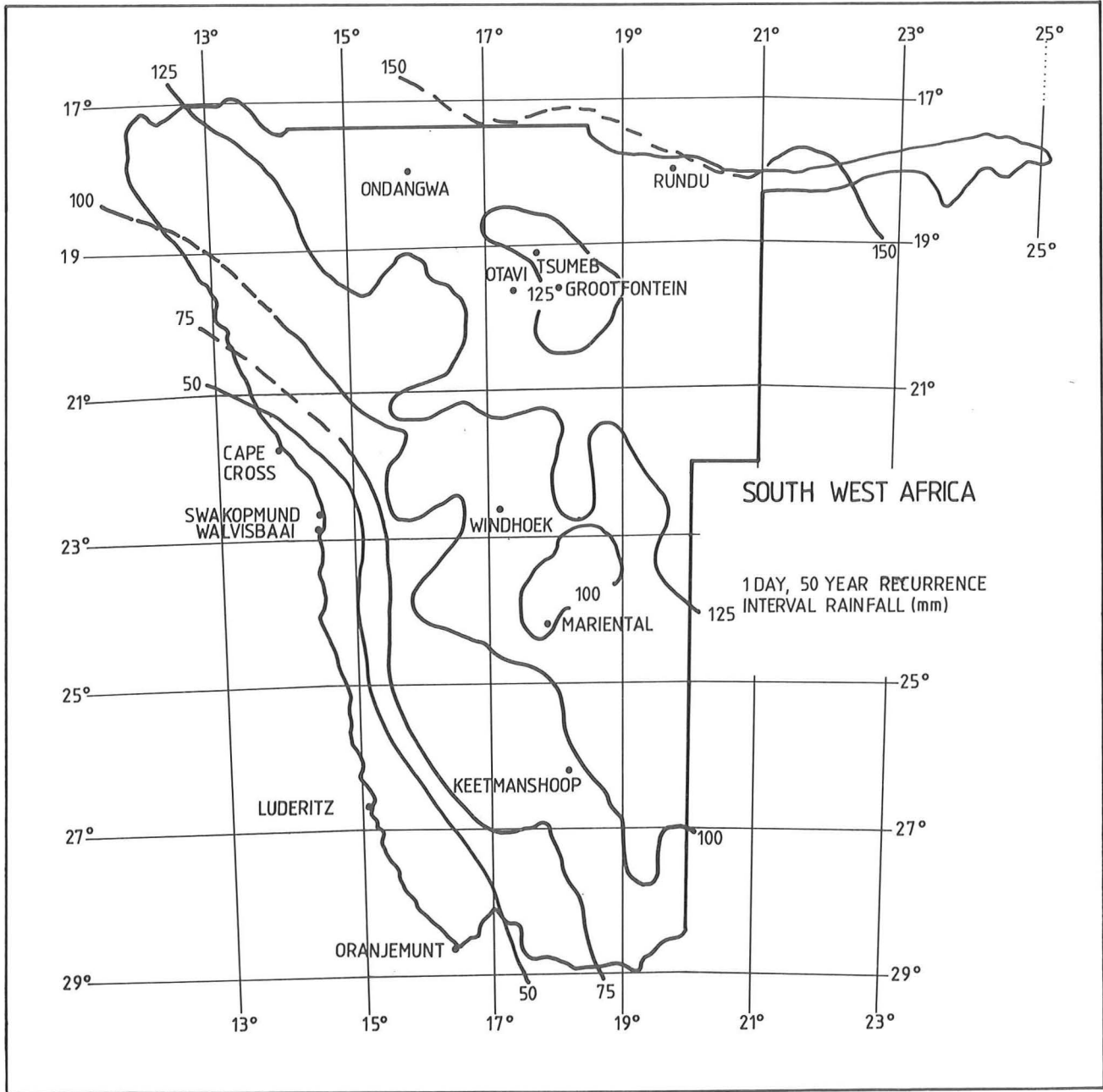




APPENDIX D3.3

MAP OF 50-YEAR RECURRENCE INTERVAL STORM RAINFALL :  
SOUTH WEST AFRICA



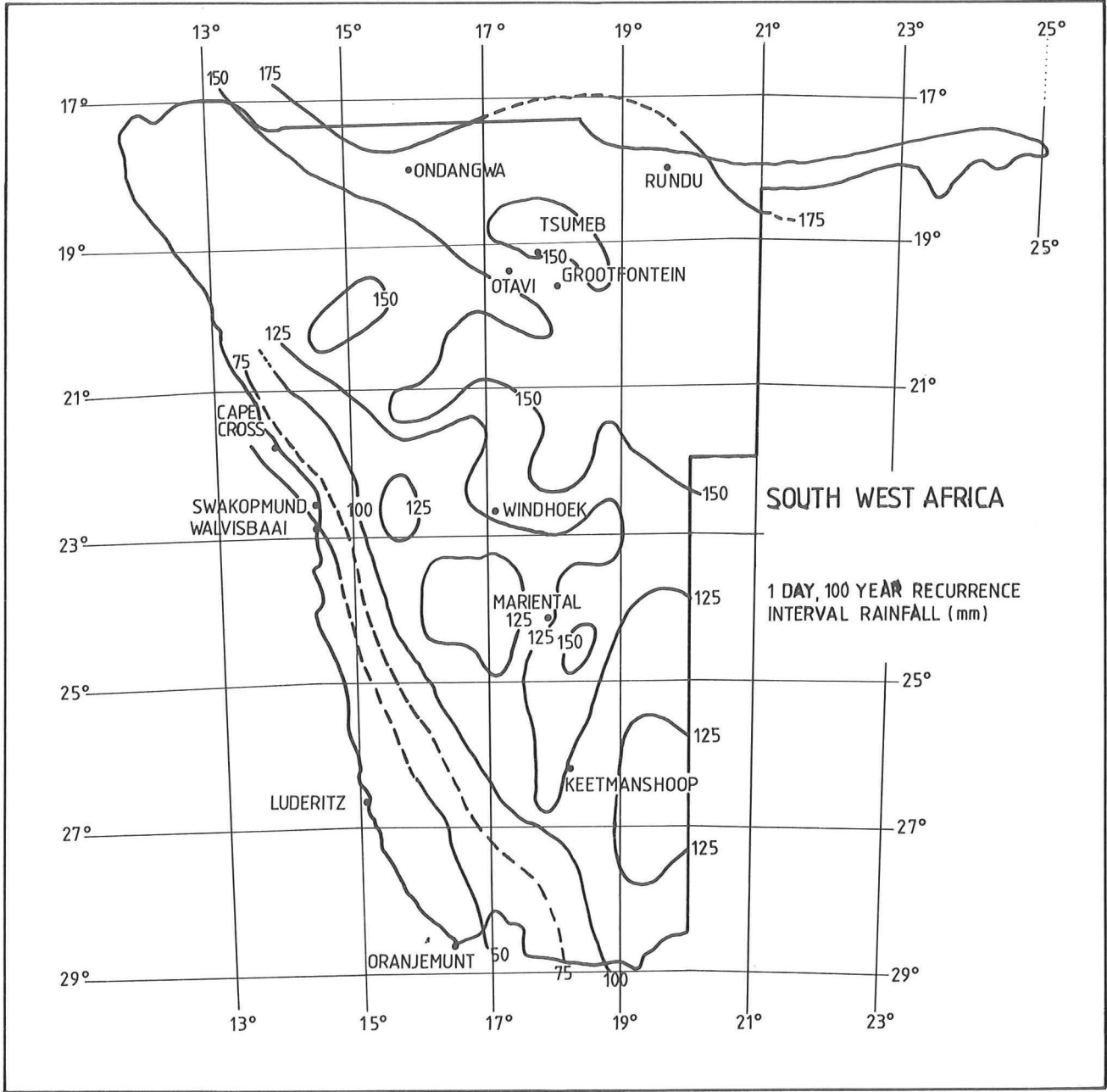




APPENDIX D3.4

MAP OF 100-YEAR RECURRENCE INTERVAL STORM RAINFALL :  
SOUTH WEST AFRICA



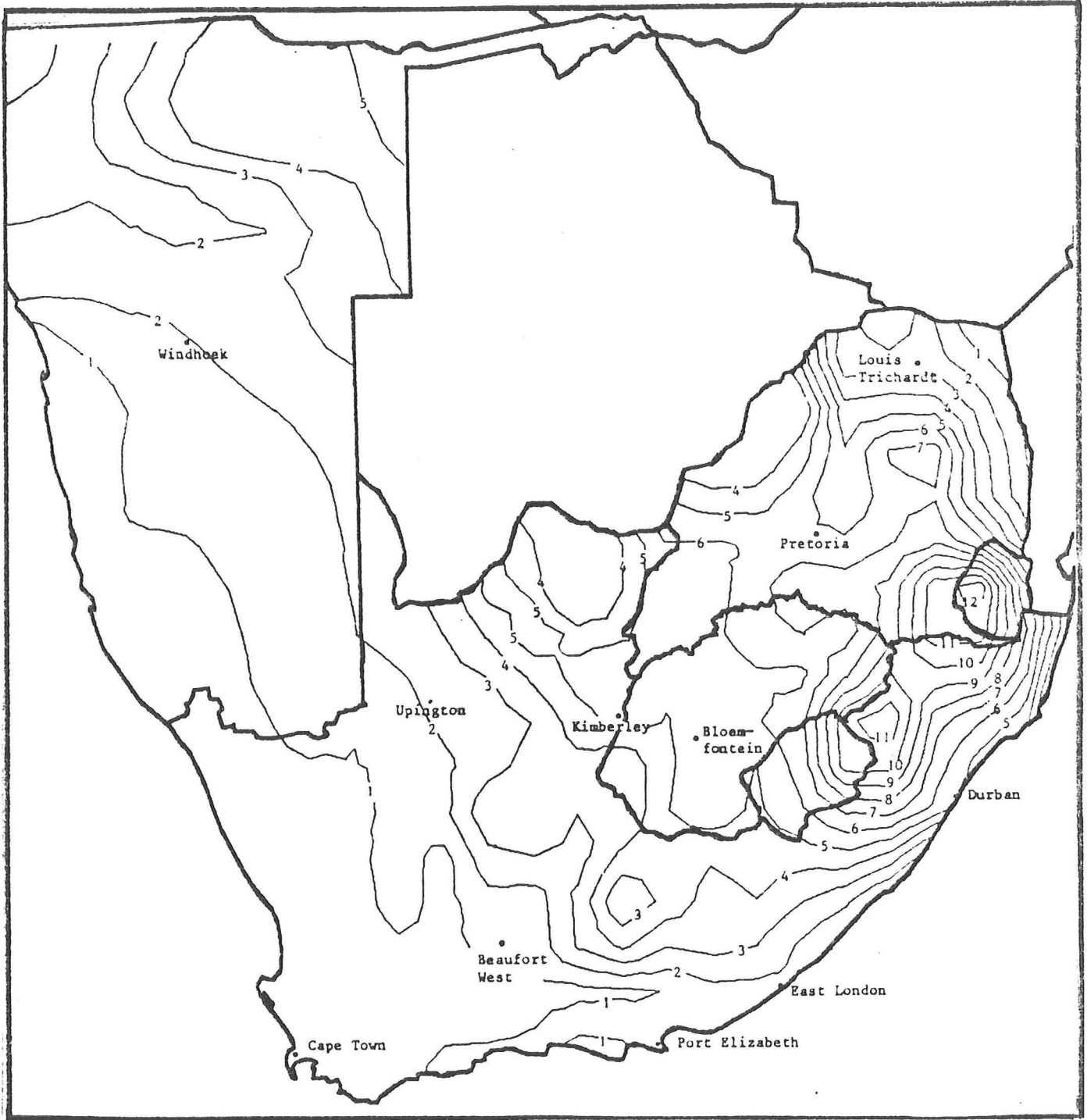






APPENDIX E

MAP OF MEAN ANNUAL INCIDENCE OF LIGHTNING GROUND  
FLASH SQUARE KILOMETER FOR SOUTH AFRICA AND  
SOUTH WEST AFRICA/NAMIBIA : SOURCE : NATIONAL  
SCIENTIFIC AND INDUSTRIAL RESEARCH, PRETORIA



MEAN ANNUAL LIGHTNING GROUND FLASH DENSITY FROM 1975 TO 1981 (FLASHES/km<sup>2</sup>/YEAR).  
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 RESEARCH, NATIONAL ELECTRICAL ENGINEERING RESEARCH INSTITUTE, PRETORIA.



