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TRANSPORT and ROAD RESEARCH LABORATORY

DEPARTMENT of the ENVIRONMENT

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THE PREDICTION OF STORM RAINFALL IN EAST AFRICA

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THE PREDICTION OF STORM RAINFALL IN EAST AFRICA

ABSTRACT

A simple method for predicting the characteristics of storms for the design of drainage structures in East Africa is described. The variation of 2 year daily point rainfall, and the 10:2 year ratio for daily rainfall, over East Africa are given in map form. Using these, daily point rainfall for any return frequency can be calculated. To arrive at the design storm the daily point rainfall is adjusted using a generalised depth-duration equation and a graphical representation of the variation of mean rainfall with area.

1. INTRODUCTION

Before the hydraulic and structural designs for a road bridge or culvert can be started, an estimate must be made of the peak flow that the structure must safely pass. If flow measurements have been made for a number of years on the river, or on a similar but adjacent river, this involves only a statistical analysis of recorded peaks to arrive at a design flood of an appropriate return frequency. In East Africa, particularly on the smaller rivers, such data rarely exist and use must be made of the much more common rainfall measurements published by the East African Meteorological Department. From rainfall records a design rainstorm is constructed and routed through a suitable catchment model to give the design flood.

Although an impressive amount of rainfall data exists, it has not been published in a form that can be readily used by highway engineers for bridge and culvert design. The purpose of this report is to extract relevant storm data from the published records and, combining these with certain unpublished data, to produce a simple method for preparing design storms for flood estimation. The method involves first estimating the 2 year, 24 hour point rainfall from a storm rainfall map of East Africa. Three adjustments are then made:

(a) Using a generalised relationship between rainfall of any return frequency and the two year values the 24 hour point rainfall for the design return frequency is calculated.

(b) A depth-duration rainfall equation is used to calculate the point rainfall for the appropriate time of concentration of the catchment.

(c) An areal reduction is read off a graph to convert this to the mean rainfall depth which is the required rainfall input for the catchment model.

2. TWO YEAR, 24 HOUR POINT RAINFALL MAP FOR EAST AFRICA

There are about 3,000 rainfall stations in East Africa which submit daily records to the Meteorological Department for subsequent publication. The distribution of these is, however, far from uniform and many have been installed only in recent years.

The advice often given to engineers requiring a design storm is to select a suitable rainfall station, on, or close to, the catchment and to analyse the records for this station. For much of East Africa a station on or close to the catchment cannot be found or, if present, it has often been recording for such a short period of years that it can give only unreliable estimates of flood producing rainfall. It was therefore decided to analyse all available published records and use these to produce maps of storm rainfall from which values for individual catchments could be interpolated.

Using records in published form this would have been a mammoth task, but fortunately early in the investigation the East African Meteorological Department transferred all their reliable daily rainfall records for the years 1957-68 and selected stations for 1926-56 to magnetic tape and gave the Laboratory permission to make a copy of the tapes.

From the first tape 867 stations which had at least 10 complete data years and from the combined tapes 99 stations with about 40 complete data years were selected. The first set of data was used to map the variation of storm rainfall over East Africa and the second to establish a means of adjusting values read off the map for alternative frequencies.

For each station selected for the first set of data the highest 24 hour fall during each calendar year was read off. These were ranked and given return frequencies using the expression:

$$T = \frac{n+1}{m}$$

where T is the return frequency in years

n is the number of years of record

and m is the ranking order, m = 1 for the largest value,

m = n for the smallest.

If the rainfall depth is plotted against the assumed return frequency a non-linear relationship becomes apparent. Many methods are available to linearise this relationship which, so long as extrapolation beyond the period of record is not attempted, give very similar results. The most commonly accepted method is the Gumbel method (1) which is of the form

$$Y = a + c \log \log \frac{T}{T-1}$$

where Y is the predicted depth of rain

T is the return frequency as previously defined

a and c are constants.

Gumbel equations for all of the stations were produced. Because of the short period of record and the known variability year to year of rainfall in East Africa, such equations are bound to be only very rough estimates of storm rainfall at return frequencies approaching the period of record. The most accurate value is likely to be near to the median value which has a return frequency of 2.3 years. For this reason a 2 year storm was selected for mapping.

The 2 year daily storm rainfall estimates and the coordinates for each station were entered into the Laboratory's 47/0 computer and a map was produced using the Calcomp General Purpose Contouring Program (GPCP). As the surface is specified by random data, the data are gridded; that is, the values of the function at the mesh points of a rectangular array are generated by a procedure which analytically constructs a smooth surface passing through every data point. The isohyets are produced by interpolation from the generated mode values of the mesh using a third order function. Among the parameters to be specified by the user of GPCP are the mesh size, and the number of data points required in the vicinity of a node in order to determine the node value. The effect of assigning various values to these parameters was investigated, and as a result suitable values were chosen.

The resulting 2 year 24 hour storm rainfall map is shown in Fig. 1.

The distribution of gauges is shown in Fig. 4 (section 3).

76 of the rainfall stations had records in both the 10 and 40 year tapes. These were used to assess the

probable errors in the individual two year estimates using the shorter period of record. The results are plotted in Fig. 2 where it will be seen that there is a considerable scatter. This is to be expected with so short a period of record. A line of best fit through the points was calculated and is shown as a full line. It will be seen that there is a tendency for the results from the 10 year tape to over estimate the 2 year storm particularly at values of 80 mm and over but the scatter of the points is such that no systematic adjustment to the map is justified. The errors are on the safe side in design and for about 80 per cent of the area are well within the plotting accuracy.

The same analysis was made for the records for each region. All were consistent with the overall results except the arid zone in North and East Kenya. Here the 10 year tape results consistently over estimated the 2 year values by about 10 mm.

The smoothing of isohyets achieved by the contouring programme should remove most of the random errors in the estimates. At this time it is not possible to check how far this has been successfully accomplished but this will become apparent if the same exercise is undertaken in 10 years time when further data are available.

Because of the uncertainty of estimation of rainfall in the arid zone of North East Kenya it is not recommended at this time that Fig. 1 be adjusted to allow for the apparent over estimate from using only 10 years of record.

Records from 8 gauges within an area close to Nairobi, for which 35 years of reliable data were available, were analysed as a further check on the probable errors in the use of short period records and to check on possible cyclic behaviour in storm rainfall in East Africa.

Running means and standard deviations for annual maxima were calculated for each gauge. From these, 95 per cent confidence bands for the means were calculated and plotted against the period of the running mean. These are shown in Table 1 and Fig. 3. (Note: the mean annual maximum rainfall has a return frequency of approximately 2.3 years).

If any significant cyclic effects were present these would show up as peaks in Fig. 3. As can be seen a smooth curve has resulted. It may therefore be concluded that cyclic effects are not significant.

From the figure the relative improvement in estimate of 2 year storms with increasing record length can be seen. Below 10 year periods the confidence limits diverge rapidly but for longer periods the improvement is less dramatic. An increase from 10 to 20 year period reduces the confidence limits by almost half which indicates the order of the improvement in estimate in areas of sparse gauge coverage which can be expected if Fig. 1 is replotted in about 10 years time when more data are available.

3. TWENTY-FOUR HOUR STORM RAINFALL FOR ANY RETURN FREQUENCY

In section 2, Gumbel Analysis was used to establish 2 year values for storm rainfall. The Gumbel equation has the form

$$y = a + c\,x$$

where y is the storm rainfall for the appropriate reduced variable x, and a and c are constants.

To use the 2 year rainfall map, Fig. 1, to predict storms of larger return frequency it is necessary to be able to predict suitable values for a and c. To attempt to do this a selection of the Gumbel regression lines from the 40 year tape were superimposed to see if there was any pattern to them. It was noticed that certain regional characteristics were evident. For example, in the arid areas and the coastal strip, slopes (c) tended to be higher than in Uganda. The gauges were therefore split up into regional groupings. Earlier analysis of data from Kenya and Uganda suggested four regional groups; the coastal strip, the arid area of north and east Kenya, the central Highlands and west of the Rift Valley. These regions were therefore used.

Linear regressions of Gumbel slope on the 2 year value (y_2) were made for each region. In two zones

TABLE 1

95 per cent Confidence half band width For Running means
of Annual Maximum Daily Rainfall

95 per cent Confidence Half Band Widths (mm)									
Gauge No.	913604	913606	913618	913620	913624	913628	913629	913630	Average
Period (yrs)									
5	2.31	3.50	4.80	5.72	3.36	3.32	6.15	6.66	4.48
6	2.03	3.15	4.55	5.47	3.08	3.11	5.68	2.78	3.73
7	1.75	3.12	4.28	5.36	2.93	2.98	5.20	2.67	3.54
8	1.30	2.87	4.10	5.13	2.68	2.61	4.64	2.57	3.24
9	1.10	2.52	3.82	4.88	2.50	2.30	3.99	2.49	2.95
10	1.02	2.20	3.69	4.65	2.25	2.06	3.46	2.38	2.72
11	1.01	2.07	3.59	4.32	2.16	2.07	2.99	2.30	2.56
12	1.14	2.04	3.57	4.04	2.13	2.20	2.56	2.30	2.50
13	1.10	2.06	3.53	3.77	2.12	2.22	2.29	2.20	2.41
14	1.09	1.93	3.41	3.41	2.06	2.22	1.96	2.11	2.27
15	0.96	1.63	3.38	3.04	2.06	2.16	1.67	2.02	2.11
16	0.76	1.43	3.31	2.64	2.00	2.13	1.45	1.97	1.96
17	0.67	1.47	3.23	2.24	1.92	2.09	1.42	1.87	1.86
18	0.58	1.35	3.15	1.81	1.79	2.00	1.65	1.76	1.76
19	0.49	1.22	2.99	1.44	1.68	1.83	1.87	1.68	1.65
20	0.53	1.09	2.78	1.31	1.51	1.67	2.14	1.57	1.57

significant correlations were obtained. In the other two, the coastal and the arid zones, the correlations were not significant but they contained only 8 and 5 gauges respectively and in the case of the coastal zone all the y_2 values were very similar.

The regression equations for the former zones were

West of Rift Valley $\quad$ Slope = $1.841 + 0.249\, y_2$

Central Highlands $\quad$ Slope = $3.051 + 0.358\, y_2$

For each of the two regression lines there was found to be no significant difference between the slope of the line as calculated and the slope of a line through the origin (o, o) and (y_2, c). It was therefore concluded that the slope of the Gumbel regression line could be replaced by a simple ratio of the values of 2 points on the regression, the 10 year and 2 year ratio ($y_{10}:y_2$) being most appropriate.

If the Gumbel equation is $y_n = a + c\,x_n$

$$y_{10} - y_2 = c\,(2.252 - 0.367)$$

$$\frac{y_{10}}{y_2} = \frac{1.885c}{y_2} + 1$$

For each zone the average value for slope (c) and y_2 were calculated and the appropriate $y_{10}:y_2$ ratio derived. These are shown below in Table 2.

TABLE 2

Zone	Average slope	Average 2 year storm	y10/y2
	(c)	(y_2)	
West of Rift Valley	17.39	62.08	1.53
Central Highlands	20.77	66.52	1.59
Arid	35.30	65.17	2.01
Coastal strip	38.02	94.51	1.76

Because of the scarcity of gauges on the 40 year tape it was necessary to use the records from the 10 year tape to establish

(a) the boundaries between zones

(b) the best value for the 10:2 year ratio particularly in the coastal and arid zones where records are very scarce, and for most of Tanzania for which no data on the 40 year tape were available.

With only 10 years of record the estimates of the 10 year storms are bound to be inaccurate, but if the scatter is random, and sufficient records are available, sufficiently accurate estimates for the appropriate value for a zone are possible. To check if using the short period of records would introduce any bias a comparison was made of the 10:2 year ratio for the 76 stations common to both tapes. The results are shown in Table 3.

With the possible exception of the arid zone, the results of which are very variable, it can be seen that no bias is likely to be introduced by using the 10 year records and a much larger number of gauges will make defining boundaries between zones easier.

3.1 Fitting of boundaries between zones

The gauge numbering adopted by the East African Meteorological Department is according to the degree square in which the gauge lies. Gauges were therefore easily grouped, and for each degree square the mean and standard deviation for the 10:2 year ratios were calculated. The means for adjacent squares were then compared to see if the differences were significant. In this way the rough boundary to the zones was established. To get a more accurate plot the gauges adjacent to the boundary were located on large scale maps and the boundary

TABLE 3

Comparison of 10:2 year ratios from 40 and 10 year tapes

	No. of stations	Mean 10:2 year ratio	95 per cent confidence half band width
West zone			
40 year	34	1.509	0.042
10 year	34	1.516	0.058
Central Highlands			
40 year	29	1.597	0.046
10 year	29	1.585	0.057
Arid zone			
40 year	5	2.006	0.264
10 year	5	1.864	0.317
Coastal strip			
40 year	8	1.728	0.098
10 year	8	1.651	0.178

fixed by inspection. Once the line had been fixed it was superimposed on mean annual rainfall and topographical maps to see if there was any physical explanation for zonal differences.

The results are shown in Table 4 and Fig. 4. In order to obtain the appropriate storm rainfall value for any given return frequency, read off from Fig. 5 the N:2 year ratio corresponding to the known 10:2 year ratio and multiply by the 2 year daily rainfall, read from Fig. 1.

4. DEPTH – DURATION – FREQUENCY RELATIONSHIPS

For most catchments, the rain falling in periods of less than one day are required. These can be estimated using daily values and a suitable depth – duration relationship. Two models were tested

(a) $I = \frac{a}{T^n}$

(b) $I = \frac{a}{(T + b)^n}$

where I = intensity in mm/hr

T = duration in hours

a, b, and n are constants.

These are discussed in turn below.

TABLE 4

10:2 year ratios for daily rainfall

Zone	No. of stations	95 per cent confidence limits for the mean Ratio	Remarks
Central Highland	271	1.60 ± 0.03	Eastern and Southern boundary follows 1 000 m countour. Western boundary follows watershed between Lake Victoria and Rift-Valley Drainage Basins.
Kenya Arid	29	1.89 ± 0.10	
Kenya Coast	43	1.68 ± 0.06	Bounded by 600 mm isohyet
Tanzania south coast	11	1.74 ± 0.12	Western boundary ill defined.
Tanzania north coast	67	1.64 ± 0.04	
Inland Tanzania and Uganda	419	1.49 ± 0.02	
Semi Arid Uganda	13	1.64 ± 0.10	Western boundary follows 1 000 mm isohyet.
Mwanza	16	1.64 ± 0.13	No obvious physical explanation. Possibly local Lake effect.

4.1 Data available

Two sets of data were used. For 23 stations intensities for several durations from 15 minutes upwards were used to select the best model. For a further 18 stations only 1 hour and 24 hour values were available. These were used to assist model calibration. Details are given in Table 5.

4.2 Model testing

4.2.1 $I = \frac{a}{T^n}$

This is a model that has been suggested by Mc Callum (3) as being appropriate for East Africa to model intensities from 15 minutes to 24 hours. Mc Callum used data from 6 stations in Kenya and Tanzania. The relationship was fitted to the highest intensity measured at each station. The period of record varied between 8 and 25 years. Because of the uncertainty about an appropriate return frequency to apply to Mc Callum's data direct comparison between his results and those given below is difficult.

The Group I data, for which durations of from 15 m – 24 hours were available, were fitted to this model for a 2 year return frequency and the results are given in Table 6.

4.2.2 $I = \frac{a}{(T + b)^n}$

This model will be seen to be a general equation which reduces to the much quoted $I = \frac{a}{T + b}$ if the

TABLE 5

Details of rainfall data used

Station	Range of duration	Source of Data
GROUP I		
BUSIA	15 m – 24 hr	Supplied by Water Development Dept. Uganda
KASESE	15 m – 2 hr	
WADELAI	15 m – 2 hr	
MUGUGA	15 m – 24 hr	Extracted from records of East African Agriculture and Forestry Research Organisation
ATUMATAK	15 m – 24 hr	
SAMBRET	15 m – 24 hr	
SAOSA	15 m – 24 hr	
EQUATOR	15 m – 1 hr	From Taylor & Lawes (2)
KABATE	15 m – 6 hr	
KISUMU	15 m – 6 hr	
KITALE	15 m – 3 hr	
MOMBASA	15 m – 6 hr	
NANYUKI	15 m – 1 hr	
VOI	15 m – 1 hr	
DAR ES SALAAM	15 m – 6 hr	
DODOMA	15 m – 3 hr	
KIGOMA	15 m – 3 hr	
MBEYA	15 m – 3 hr	
TABOCA	15 m – 6 hr	
ZANZIBAR	15 m – 6 hr	
ENTEBBE	15 m – 6 hr	
GULU	15 m – 3 hr	
KAMPALA	15 m – 3 hr	
GROUP II		
KITALE	1 hr and 24 hr	Extracted from records of East African Met. Dept.
MOLO		
LAMU		
LODWAR		
GARISSA		
NAKURU		
KISUMU		
MOMBASA		
NANYUKI		
VOI		
JINJA		
MBARARA		
TORORO		
KAMPALA		
GULU		
ENTEBBE		
FORT PORTAL		

For each duration the largest rainfall value in each calendar year was ranked to form an annual series for the station. Estimates of rainfall depth corresponding to recurrence intervals of 2, 5 and 10 years were then made using the Gumbel method (1). The period of record for the group 1 stations was between 8-35 years, and the group 2 stations were all of 20 years.

TABLE 6

Two year intensity – duration relationships ($I = \frac{a}{T^n}$ model)

Station	Intensity – Duration Relationship	Correlation coefficient
BUSIA	$I = 49.12T^{-0.83}$	– 0.994
MUGUGA	$I = 28.09T^{-0.69}$	– 0.994
ATUMATAK	$I = 32.34T^{-0.86}$	– 0.994
SAMBRET	$I = 37.73T^{-0.83}$	– 0.997
SAOSA	$I = 37.96T^{-0.81}$	– 0.997

index n = 1. Often the simpler form is used with different values for the constants for different ranges of duration. Where, as in East Africa very little data other than daily totals exist, a relationship containing a discontinuity is difficult to fit and the general expression, even if slightly more difficult to apply in practice, is to be preferred.

The Group I data were fitted to the model for a number of alternative values of the constant 'b' between 0.2 and 1.0 hours. The optimum value varied between stations but as no regional pattern to this variation could be found it was assumed to be due to random errors in the data and an average value of b = 0.33 hrs was selected for further modelling. The results of fitting this model to the 5 stations, for which complete data were available, were very much superior to the previous model. It was therefore adopted and used with all group I stations. The derived relationships with b = 0.33 hrs are given in Table 7.

4.3 Further calibration using hourly and daily data

Hourly and daily estimates of rainfall with 2, 5 and 10 year recurrence intervals were available for 18 stations covering all the climatic zones of Kenya and Uganda. These were fitted to the intensity – duration model with the constant being equal to 0.33. The results are shown in Table 8.

4.4 General depth – duration model for East Africa

Tables 7 and 8 show that a constant value for "n" cannot apply to the whole of East Africa. The area was therefore once again split up into zones. Four zones were considered:–

(a) Coastal strip

(b) Arid

(c) Central Highlands

(d) Inland (all other zones on Fig. 4)

It will be seen that for most of the stations in the Inland and Arid zones the value of 'n' is approximately 1.0 but that lower values are typical for the Coastal and Central Highland areas.

For the Inland zone, only Entebbe gave a value for 'n' well under 1.0. A possible explanation for this is that the period of record included one very large storm which it has been estimated approached the probable maximum precipitation (4). This would result in an under estimation of the time value of 'n'. There is therefore no firm evidence for excluding Entebbe from the general inland model.

TABLE 7

Values of constants in intensity – duration relationships for Group I Stations

$$I = \frac{a}{(T+\frac{1}{3})^n}$$

Station	2 year		5 year		10 year		2 yr correlation coefficient
	a	n	a	n	a	n	
BUSIA	74.62	1.00	94.88	0.97	105.19	0.96	– 0.9998
MUGUGA	40.18	0.83	54.86	0.84	63.75	0.85	– 0.9996
ATUMATAK	51.06	1.01	61.33	0.99	68.74	0.97	– 0.9999
SAMBRET	56.61	1.00	70.34	0.97	77.98	0.96	– 0.9996
SAOSA	56.55	0.98	69.35	0.92	81.39	0.90	– 0.9997
KASESE	54.95	1.09	66.65	1.04	73.81	1.01	
WADELAI	57.87	0.98	72.24	0.82	81.69	0.75	
EQUATOR	40.03	0.99	48.53	1.02	54.90	1.03	
KABETE	42.17	0.78	50.24	0.83	59.64	0.84	
KISUMU	72.15	1.01	86.39	0.99	96.36	0.98	
KITALE	49.90	0.99	62.90	1.01	70.79	1.01	
MOMBASA	49.49	0.78	65.88	0.77	74.48	0.83	
NANYUKI	44.34	0.92	57.81	0.81	65.09	0.80	
VOI	53.39	0.84	79.04	0.57	95.34	0.48	
DAR ES SALAAM	57.83	0.91	68.83	0.86	77.41	0.84	
DODOMA	55.35	0.95	71.28	0.91	82.43	0.88	
KIGOMA	58.51	0.97	74.79	0.88	83.89	0.86	
MBEYA	42.20	0.97	55.62	0.97	64.16	0.98	
TABORA	55.20	1.00	70.84	1.02	82.52	1.03	
ZANZIBAR	59.83	0.81	76.06	0.72	86.29	0.69	
ENTEBBE	63.16	0.88	82.70	0.89	92.85	0.88	
KAMPALA	58.52	0.97	73.24	0.95	83.36	0.94	
GULU	70.06	1.01	87.96	0.98	100.83	0.96	

2 yr correlation coefficient is shown only for 5 stations for comparison with TABLE 6

TABLE 8

Values of constants in intensity – duration relationships for Group II Stations

$$\text{Model I} = \frac{a}{(T + \frac{1}{3})^n}$$

Station	2 year		5 year		10 year	
	a	n	a	n	a	n
KITALE	51.50	0.97	65.41	0.94	74.52	0.93
MOLO	34.38	0.89	51.11	0.94	62.38	0.96
LAMU	47.04	0.77	61.08	0.70	70.84	0.67
LODWAR	47.35	1.02	58.36	0.97	65.89	0.95
GARISSA	55.33	1.00	81.42	0.99	99.19	0.98
NARKURU	46.06	0.97	60.63	0.99	71.21	0.99
KISUMU	70.49	0.97	84.95	0.97	95.26	0.96
MOMBASA	46.14	0.84	57.85	0.80	65.02	0.79
NANYUKI	43.13	1.00	60.96	1.05	73.20	1.07
VOI	53.76	0.94	83.36	0.96	103.10	0.97
JINJA	65.43	1.00	73.28	0.96	78.80	0.94
FORT PORTAL	49.24	0.98	65.26	0.99	76.30	0.99
MBARARA	51.27	0.96	69.94	0.95	81.99	0.95
TORORO	71.97	1.01	89.00	0.98	99.80	0.97
ENTEBBE	76.04	0.96	97.09	0.88	112.12	0.86
KAMPALA	60.80	1.00	76.59	1.01	87.52	1.01
GULU	60.84	0.97	84.12	1.00	97.75	1.01
NAIROBI	50.07	0.86	62.26	0.88	70.79	0.87

The 'n' values for the Central Highlands are very variable. The western stations (Equator and Nakuru) give very similar results to Inland stations whereas stations around Nairobi give much lower values. The explanation for this must be differences in synoptic weather processes. This can be checked by looking at the diurnal variations in rainfall occurrence which have been studied by Thompson (5). The conventional "continental" rainfall model gives convective thunderstorms in late afternoon. Much of the inland zone does have a rainfall maximum at this time as does the northern and western parts of the Central Highlands zone, but in the Nairobi area heavy rain occurs in the evening, spreading through to the early morning in the "short rains" (November). Thompson claims that a large part of this rain results from the spread of storms from the Highlands close by after about 5.00 pm. This would explain the longer duration and lower intensity (small 'n') of Nairobi rainfall. A similar pattern would be expected on all windward slopes of the Kenya – Aberdare range and the Kilimanjaro area. The Central Highlands zone has therefore been divided into two halves (by the dotted line in Fig. 4) to show the area similar to Nairobi and the area similar to the inland stations.

Molo is the one station that does not fit this pattern. It is on the eastern facing slope of the Mau plateau and at an altitude of 2,500 m, but on the evidence of just one station it is not possible to draw any firm conclusions.

Voi does not fit the arid model. Thompson (5) shows that although much of the rain at Voi occurs in the afternoon, there is a significant amount of morning rainfall due possibly to the effect of the adjacent Taita hills. Voi's position (Fig. 4) on the border between the arid and highland zones is appropriate and Voi is therefore not included in computing average values for 'n' below.

At the coast thunderstorms are not very common and heavy rainfall is more frequently the result of a disturbance or discontinuity in the monsoon (13). A different model for the coast is therefore appropriate.

Having defined 3 zones, average values for 'n' were calculated.

TABLE 9

Average values for the index 'n'

in the equation $I = \dfrac{a}{(T + \frac{1}{3})^n}$

	Recurrence Interval		
	2 year	5 year	10 year
1. Inland stations	0.98	0.96	0.96
2. Coastal stations	0.82	0.76	0.76
3. Eastern slopes of Kenya-Aberdare Range	0.82	0.85	0.85

It is proposed that in practice an engineer will estimate the daily rainfall for the appropriate recurrence interval using Figs. 1, 4 and 5. He will then enter this into the relevant intensity – duration model above, to obtain the design rainfall he requires. The form of the above models were therefore adjusted to simplify this operation.

$$I = \frac{a}{(T + b)^n}$$

Rainfall in time T (R_T) $= \dfrac{aT}{(T + b)^n}$

The daily total (R_D) $= \dfrac{24\,a}{(24 + b)^n}$

Eliminating 'a' $R_T = \dfrac{T}{24} \left(\dfrac{24 + b}{T + b}\right)^n R_D$

with b = 0.33, a unique set of curves can be developed for converting daily rainfall to rainfall of any given duration. These are shown in Fig. 6.

4.5 Conclusions

It was concluded that Fig. 6 is the best means at present available for estimating depth – duration ratios for rainfall in East Africa. All inland areas other than Eastern and South Eastern facing slopes of the Aberdare – Kenya ranges are satisfactorily modelled using the average inland curves. It is possible that in very wet mountainous areas elsewhere curves similar to the Nairobi curve are appropriate but these areas will be very limited in extent and with present data impossible to predict. In these areas use of the average inland curve is probably conservative.

5. AREA REDUCTION FACTORS

In the previous sections a method has been developed for predicting point rainfall for any duration and recurrence interval. Over a catchment the point rainfall will vary and it is necessary to be able to predict this variation to estimate the volumetric rainfall input to the catchment. The most convenient way is by means of areal reduction factors (ARF). These are factors by which the appropriate estimates of point rainfall are multiplied to give the average depth of rainfall over the catchment.

No factors have been published for East African data. In this section data from four dense networks of raingauges in East Africa are analysed to derive areal reduction factors and from them a general equation for East Africa is developed. This is then compared to published equations for other parts of the world.

5.1 Area Reduction Factors for East African Raingauge Networks

5.1.1 The Kakira Network Sixteen years of record from 29 standard daily read raingauges were available from a sugar estate on the northern shore of Lake Victoria, 12 miles east of Jinja, Uganda. The estate is approximately 82 km^2 in area and undulating. The gauge network is shown in Fig. 7.

The method adopted for deriving the areal reduction factors in this and the following network studies was to derive depth-frequency equations for point rainfall for each gauge and to compare these with similar equations for the average rainfall over the catchment.

Depth-frequency equations for each of the 29 gauges were obtained using the Gumbel method (1). Annual series were formed by ranking the maximum 1 day rainfall for each calendar year, for the 16 years. These were plotted on Gumbel extreme value paper to provide a visual check on the assumption of linearity. All gave reasonable straight line plots. The Gumbel regression lines were then calculated. Goodness of fit was checked by calculating the correlation coefficients as described by Nash (6) and these are given in Table 10.

Over the network the point data relationships were averaged to give the best estimate of the depth-frequency characteristics of the area. To do this one must assume that the area is homogeneous and that differences between gauges can be reasonably expected to be due to chance. This was checked by using the Langbein homogeneity test (7). The equation for point rainfall for the whole network is also given in Table 10.

The network was divided up into six areas labelled A – F in Fig. 7. The mean areal rainfall was calculated for the following combinations of area:

(a) Areas A, B, C, D, E and F (approx. 15 km^2)

(b) Areas A + B + C and D + E + F (approx. 40 km^2)

(c) Total network (approx. 80 km^2).

The mean rainfall for each area was calculated for each day of heavy rainfall using the Thiessen method (14). Annual series were formed for these and Gumbel regression equations computed as before. These are shown in Table 11.

By comparing these regression equations with the mean equations for point rainfall, areal reduction factors were calculated. These are given in Table 12, and shown also in Figs. 8 to 10.

There is no evidence for a change in areal reduction factor with recurrence interval, bearing in mind the width of the confidence band. The regressions are likely to be most accurate at a recurrence interval of just over two years. The two year values were therefore taken as the best estimate of areal reduction factor for all recurrence intervals.

TABLE 10

Kakira Network

Regression equations for daily point rainfall

Gauge No.	Regression equation	Correlation coefficient (r)	Estimated daily rainfall (mm) for given return frequency 2 yr	5 yr	10 yr	20 yr
1	Y = 47.07 + 16.30 X	0.988	53.05	71.52	83.78	95.53
2	Y = 51.35 + 14.53 X	0.962	56.68	73.15	84.07	94.55
3	Y = 49.81 + 11.81 X	0.985	54.15	67.54	76.42	84.93
4	Y = 49.93 + 19.26 X	0.978	53.70	65.32	73.04	80.43
5	Y = 49.53 + 8.02 X	0.983	52.47	61.56	67.59	73.37
6	Y = 52.81 + 18.81 X	0.963	59.71	81.08	95.17	108.73
7	Y = 50.07 + 13.94 X	0.953	55.19	70.98	81.46	91.31
8	Y = 52.43 + 8.63 X	0.989	55.60	65.38	71.86	78.09
9	Y = 50.71 + 14.03 X	0.949	55.86	71.76	82.31	92.42
10	Y = 53.74 + 12.37 X	0.987	58.28	72.30	81.60	90.52
11	Y = 52.54 + 13.54 X	0.966	57.51	72.85	83.03	92.79
12	Y = 52.10 + 15.05 X	0.982	57.62	74.68	85.99	96.84
13	Y = 54.78 + 15.03 X	0.966	60.30	77.33	88.63	99.46
14	Y = 55.51 + 17.73 X	0.971	62.02	82.11	95.44	108.22
15	Y = 53.56 + 12.68 X	0.983	58.21	72.58	82.12	91.26
16	Y = 53.81 + 11.36 X	0.993	57.98	70.85	79.39	87.58
17	Y = 61.12 + 16.16 X	0.970	67.05	85.36	97.51	109.16
18	Y = 53.06 + 12.96 X	0.982	57.82	72.50	82.25	91.58
19	Y = 55.69 + 18.37 X	0.982	62.43	83.25	97.06	110.30
20	Y = 55.88 + 18.27 X	0.966	62.59	83.29	97.02	110.20
21	Y = 53.75 + 12.27 X	0.989	58.25	72.16	81.38	90.23
22	Y = 54.86 + 10.79 X	0.993	58.82	71.05	79.16	86.94
23	Y = 52.81 + 16.13 X	0.965	58.73	77.01	89.13	100.76
24	Y = 52.97 + 13.14 X	0.984	57.79	72.68	72.56	92.04
25	Y = 55.09 + 15.31 X	0.986	60.71	78.06	89.57	100.61
26	Y = 50.59 + 7.40 X	0.957	53.31	61.69	67.25	72.59
27	Y = 53.33 + 13.28 X	0.977	58.20	73.25	83.23	92.81
28	Y = 50.91 + 17.44 X	0.929	57.31	77.07	90.18	102.76
29	Y = 59.09 + 17.64 X	0.959	65.56	85.55	98.82	111.53
Mean equation	Y = 53.06 + 13.95 X	0.997	58.19	73.96	84.46	94.51

Notes: Y = Maximum expected daily point rainfall in T years (mm)

$X = -(0.834 + 2.303 \log\log \frac{T}{T-1})$ where T is the return frequency (yrs)

TABLE 11

Kakira Network

Regression equations for mean areal daily rainfall

Area	Regression equation	Correlation coefficient (r)	Estimated areal rainfall (mm) for given return frequency 2 yr	5 yr	10 yr	20 yr
A	Y = 47.93 + 11.07 X	0.978	51.99	64.54	72.86	80.84
B	Y = 49.85 + 6.30 X	0.979	52.16	59.30	65.04	68.58
C	Y = 46.50 + 12.01 X	0.982	50.91	64.52	73.55	82.21
D	Y = 47.97 + 13.94 X	0.987	53.13	68.88	80.36	89.41
E	Y = 45.29 + 13.80 X	0.975	50.35	65.99	76.37	86.32
F	Y = 52.36 + 13.53 X	0.990	57.33	72.66	82.83	92.58
A + B + C	Y = 45.68 + 8.87 X	0.977	48.94	58.99	65.66	72.05
D + E + F	Y = 45.90 + 13.06 X	0.991	50.69	65.49	75.31	84.73
Mean for 15 km^2	Y = 48.31 + 11.77 X	0.995	52.63	65.97	74.82	83.30
Mean for 40 km^2	Y = 45.79 + 10.98 X	0.965	49.82	62.26	70.52	78.43
Total Network	Y = 42.29 + 11.11 X	0.977	46.37	58.95	67.31	75.32

TABLE 12

Kakira Network

Areal reduction factors

Area (km^2)	Areal Reduction Factor 2 yr	5 yr	10 yr
15	0.904	0.892	0.886
40	0.856	0.842	0.835
80	0.797	0.797	0.797

5.1.2 The Nairobi Network Close networks of well maintained raingauges set out at a uniform spacing, such as the Kakira network, are rare in East Africa. The bulk of the records that are available are either from widely spaced East African Meteorological Department stations or from volunteer observers at schools, railway stations, farms and private houses. The spacing of these over the country is also very wide except in a few areas, generally rich farming areas where large long established farms exist. The most densely gauged area is around Nairobi, the capital city of Kenya. Here the raingauge density is insufficient to study small area factors but is adequate to calculate average rainfall over areas of 100 km^2 and larger.

Fig. 11 shows the network of gauges and the outline of the areas over which mean rainfall was calculated. The areas are:

A	100 km^2	B + C	600 km^2
B, C	300 km^2	D	1200 km^2

TABLE 13

Nairobi Network

Regression equations for point daily rainfall

Gauge No.	Gumbel Regression equation	Correlation coefficient	Estimated storm rainfall		
			2 yr (mm)	5 yr (mm)	10 yr (mm)
3	Y = 59.66 + 23.37 X	0.95	68.2	94.7	112.3
4	Y = 54.61 + 15.62 X	0.99	60.3	78.0	89.8
6	Y = 59.72 + 18.64 X	0.98	66.6	87.7	101.7
10	Y = 59.28 + 24.43 X	0.98	68.2	95.9	114.3
13	Y = 53.01 + 24.87 X	0.99	62.1	90.3	109.0
14	Y = 58.47 + 19.00 X	0.98	65.4	87.0	101.3
15	Y = 61.90 + 23.22 X	0.93	70.4	96.7	114.2
18	Y = 58.57 + 25.63 X	0.97	68.0	97.0	116.3
20	Y = 49.56 + 21.89 X	0.96	57.6	82.4	98.9
22	Y = 57.15 + 16.46 X	0.96	63.2	81.8	94.2
24	Y = 51.64 + 13.41 X	0.97	56.6	71.8	81.8
26	Y = 54.03 + 22.53 X	0.98	62.3	87.8	104.8
27	Y = 62.26 + 30.12 X	0.94	73.3	107.4	130.1
28	Y = 58.09 + 22.02 X	0.99	66.2	91.1	107.7
29	Y = 56.13 + 22.83 X	0.97	64.5	90.4	107.5
30	Y = 48.21 + 12.07 X	0.99	52.6	66.3	75.4
35	Y = 53.19 + 19.43 X	0.99	60.3	82.3	96.9
48	Y = 55.30 + 37.69 X	0.95	69.1	111.8	140.2
Total Network	Y = 56.20 + 21.77 X	0.91	64.2	88.9	105.2

Note: Y = daily storm rainfall (mm) for given recurrence interval.

X = reduced variable as defined in Table 10.

The area C was arranged to include the whole of the built up area of the city of Nairobi (shown in Fig. 11 by a full line) so that by comparison with area B any effect on areal reduction factors due to the modifications of the climate locally by urbanisation would be shown up. As will be seen below no effect was observed.

A major difficulty in calculating rainfall for such a network is that the number of gauges in operation varies from storm to storm. Manual calculation of the Thiessen weightings for over 100 storms is very tedious. A computer program was therefore prepared which, given the co-ordinates and catch for each gauge in operation for a particular storm, calculates the appropriate Thiessen weightings and average depth of rainfall for any area. (8).

A second difficulty is that as continuous records are not available for all gauges, point rainfall relationships can only be calculated for the few gauges for which continuous records are available. For the Nairobi network 18 gauges were available with continuous records for the 20 year study period 1937-56. This period was chosen because prior to 1937 relatively few gauges were installed and for the years 1957-60 only a selection of gauge records were published.

The Gumbel regression equations for the index gauges are given in Table 13. A Langbein homogeneity test on the data showed that the area could be considered as homogeneous. The data were therefore combined to produce a Gumbel regression equation for the whole area. This is also given in Table.13.

Using the Thiessen Polygon program the average rainfall for each area was calculated for all large storms. Annual series were then prepared and Gumbel regression equations for areal rainfall calculated. These are shown in Table 14.

TABLE 14

Nairobi Network

Regression equations for areal rainfall

Area	Gumbel Regression equation	Correlation coefficient	Estimated Storm Rainfall		
			2 yr (mm)	5 yr (mm)	10 yr (mm)
A	Y = 47.02 + 19.91 X	0.99	54.3	76.9	91.9
B	Y = 46.52 + 14.60 X	0.99	51.9	68.4	79.4
C	Y = 45.73 + 16.57 X	0.99	51.8	70.6	83.1
B + C	Y = 42.65 + 14.79 X	0.96	48.1	64.8	76.0
D	Y = 37.19 + 12.53 X	0.98	41.8	56.0	65.4

TABLE 15

Nairobi Network

Areal reduction factors

Area	Area (sq km)	Areal Reduction Factor		
		2 yr	5 yr	10 yr
A	100	0.846	0.865	0.874
B	300	0.808	0.769	0.755
C	300	0.807	0.794	0.790
B + C	600	0.749	0.729	0.722
D	1 200	0.651	0.630	0.622

From the results in Tables 13 and 14 areal reduction factors were calculated and are given in Table 15. The regression equations and associated 95 per cent confidence limits are shown in Fig. 12-16.

As with the Kakira network the evidence for a variation in areal reduction factor with recurrence interval is inconclusive. The 2 year values are therefore taken as the best estimate for all recurrence intervals.

5.1.3 Sambret Network In this and the next section, 2 raingauge networks on experimental catchments installed by the East African Agriculture and Forestry Research Organisation are studied. The Sambret catchment is 6.9 km^2 in area, close to Kericho in Western Kenya. The period of record available was 1960-66 from a network of 17 standard raingauges evenly distributed over the catchment.

The analysis using the same methods as described for the Kakira network resulted in the following Gumbel regression equations:

Regression equation for point rainfall (using 17 gauges): $y = 52.45 + 14.22\,x$, $r = 0.94$

Regression equation for areal rainfall: $y = 47.88 + 14.35\,x$, $r = 0.93$

The areal reduction factors are shown in Table 16.

TABLE 16

Areal reduction factors for the Sambret catchments

Return period (yrs)	Predicted Rainfall		Areal Reduction Factor
	Point (mm)	Areal (mm)	
2	57.68	53.14	0.921
5	73.79	69.42	0.941
10	84.48	80.19	0.949

5.1.4 Atumatak Network The Atumatak catchments are situated in South Karamoja in Eastern Uganda. The area is semi-arid. The network covers an area of 8.1 km^2 and contains 23 evenly spaced raingauges. Records were available for 9 years from 1958-66. Five of the gauges were autographic raingauges from which records of point and mean rainfall for periods less than 24 hours could be extracted. Unfortunately, due to vandalism, several of the autographic gauges were out of action for most of 1962-63. Only 7 years were therefore analysed for periods shorter than 1 day.

Gumbel regression equations for point and areal rainfall were calculated as before and are given in Tables 17 and 18. The areal reduction factors from these are given in Table 19.

TABLE 17

Atumatak Network

Regression equations for point rainfall

Period (hrs)	Regression equation	Regression coefficient	Estimated Storm Rainfall		
			2 yr (mm)	5 yr (mm)	10 yr (mm)
¼	Y = 19.14 + 4.61 X	0.86	20.83	26.06	29.51
½	Y = 26.69 + 5.38 X	0.86	28.66	34.76	38.80
1	Y = 32.10 + 7.01 X	0.73	34.67	42.62	47.87
2	Y = 35.39 + 6.47 X	0.71	37.76	45.10	49.95
8	Y = 40.22 + 8.08 X	0.80	43.19	52.34	58.40
24	Y = 42.01 + 8.63 X	0.71	45.18	54.96	61.43

TABLE 18

Atumatak Network

Regression equations for areal rainfall

Period (hrs)	Regression equation	Regression coefficient	Estimated Storm Rainfall		
			2 yr (mm)	5 yr (mm)	10 yr (mm)
¼	Y = 9.95 + 3.62 X	0.95	11.28	15.38	18.10
½	Y = 16.03 + 5.49 X	0.95	18.04	24.27	28.38
1	Y = 23.07 + 6.11 X	0.93	25.31	32.24	36.82
2	Y = 27.15 + 5.65 X	0.93	29.22	35.63	39.86
8	Y = 32.87 + 6.23 X	0.98	35.16	42.22	46.89
24	Y = 35.46 + 8.33 X	0.98	38.52	47.96	54.22

TABLE 19

Atumatak Network

Areal reduction factors

Period (hrs)	Areal Reduction Factors		
	2 yr	5 yr	10 yr
¼	0.542	0.590	0.613
½	0.629	0.698	0.731
1	0.730	0.756	0.769
2	0.774	0.790	0.798
8	0.814	0.807	0.803
24	0.853	0.873	0.883

5.2 General equation for areal reduction factors

With data from only four networks it is not possible to arrive at a number of models for areal rainfall and an objective plot of the boundaries of the zones appropriate to each model. All that can be done at this stage is to develop a single model and to apply this in all cases where it is not obviously inappropriate.

Further data will become available when analysis is complete on three dense networks of autographic gauges over Nairobi, Kampala and Dar es Salaam and the networks of the Kenya and Uganda Rural Catchment programme (9). At that time an improved model will be possible.

A plot of 24 hour areal reduction factors against area (Fig. 17) shows that the two Uganda networks (Kakira and Atumatak) give smaller values than the two Kenyan networks. This is consistent with the observations of Johnson (15) who divided East Africa up into four zones.

a. Highland regions of Kenya and Southern Tanzania where rain tends to be widespread.

b. Uganda where scattered showers predominate.

c. Dry regions of N.E. Kenya and S.W. Tanzania which are intermediate between these two zones.

d. The coastal strips.

It is therefore concluded that the Sambret and Nairobi results can be combined to form an upper limit curve which will apply to highland areas of Kenya and Tanzania. The same curve will probably not be too conservative for all other areas except Uganda where the results from Kakira and Atumatak should be used as a guide until such time as further data are available.

Factors for periods of less than 24 hours are much smaller. This is particularly important for urban catchments which is one of the main reasons for initiating the urban raingauge networks referred to above. For rural areas the lag in runoff means that most storms are shorter than the time of concentration of the catchment so that 24 hour values are appropriate.

5.3 Comparison with published areal reduction factor

Very few published data are available for tropical Africa and the equations published for other parts of the world are of little use in interpreting African results because the rainfall elsewhere appears to be much more extensive. For example the equation published by the U.S. Weather Bureau (12) as being appropriate to continental U.S.A. is:

$$ARF = 1 - e^{-1.1tr^{1/4}} + e^{(-1.1tr^{1/4} - 0.01A)}$$

where tr = period (hrs)

and A = Area (sq. miles)

The factors predicted by this equation are much higher than those appropriate to East Africa. (The 1 000 km 24 hour value = 0.91).

Bruce and Clark (10) quote an equation appropriate for India.

$$ARF = 1 - C\sqrt{A}$$

where A = area in sq. miles

C = a constant which varies from 0.00275 – 0.00470

This gives values as high or even higher than the U.S. Weather Bureau equation.

The only published figures for Tropical Africa known to the authors are those by Rodier and Auvray (11) for West Africa. These are shown in the Table 20 below.

TABLE 20

10 year areal reduction factors for West Africa

Area (km^2)	10 yr Areal Reduction Factor
0-25	1
26-50	0.95
51-100	0.90
101-150	0.85
151-200	0.80

These are similar to the East African upper limit curve. It is difficult however to make a direct comparison as they are design recommendations and not experimental values and it is possible that some rounding up has been allowed to simplify design techniques.

6. CONCLUSIONS

It has been shown that daily point rainfall can be predicted for any catchment in East Africa using Figs. 1, 4 and 5. Figs. 1 and 4 are in such a form that they can be updated when the East African Meteorological Department's taped daily records have been extended. It is recommended that the mapping be repeated in about 1978 when the short period tape will cover a 20 year period.

The depth-duration-frequency equations are adequate for design use for flood prediction in rural areas. They are not adequate for use with urban flood models but this will be rectified when current research in East Africa using high speed autographic recorders is complete. Improved models for short duration rainfall should therefore be available by early 1975.

Further data are required to give a complete picture of the variation of areal reduction factor with location and storm duration. These will be made available by the current rural catchment and urban rain gauge programme, which it is anticipated will be reported upon early in 1975.

7. ACKNOWLEDGEMENTS

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9. APPENDIX 1

Design curves and worked examples

The relevant figures and table are reproduced below. These examples were designed to act as a guide to the design methods developed in the main report and also to show the range of variation in short period rainfall over East Africa.

Example I

Calculate the design storm required to estimate the flood resulting from 25 year recurrence interval storm rainfall on a 20 km^2 catchment, grid reference 32°E 1°N.

Locate the catchment on Appendix 1 Fig. 1 (marked with C) The 2 year 24 hr rainfall = 70 mm	70 mm
Locate catchment on Appendix 1 Fig. 2 (marked with C) 10 year: 2 year ratio is Group 6 Inland = 1.49	1.49
From Appendix 1 Fig. 3 for a 10 year: 2 year ratio of 1.49 and a recurrence interval of 25 years the flood factor = 1.74	1.74
The 25 year 24 hour point rainfall = 1.74 x 70 mm = 121.8 (say 122)	122 mm
From Appendix 1 Fig. 4 read off the area reduction factor for a 20 km^2 area = 0.9	0.9
The areal rainfall for the catchment is 122 x 0.9 = 109.8 (say 110)	110 mm
From Appendix 1 Table 1 select a suitable 'n' value for an inland station (Zone 1) = 0.96	0.96

Using 'n' = 0.95 in Appendix 1 Fig. 5 select rainfall ratios for 15 mins, 30 mins, 1 hour, 2 hours, 4 hours and multiply by 110 mm to obtain R_T for each period. These are then plotted as a symmetrical histogram, R_T being shown in units of (mm of rain in 15 mins)

15 mins	0.36 x 110 R_T = 39.6	$R_T = 39.6$
30 mins	0.51 x 110 R_T = 56.1	$R_T = 56.1 - 39.6 = 16.5$
1 hour	0.655 x 110 R_T = 72.05	$R_T = \frac{72.1 - 56.1}{2} = 8.0$
2 hour	0.825 x 110 R_T = 90.75	$R_T = \frac{90.8 - 72.1}{4} = 4.7$
4 hour	0.855 x 110 R_T = 94.05	$R_T = \frac{94.1 - 90.8}{8} = 0.4$

These values are shown plotted on Appendix 1 Fig. 6(a).

Example II

Assuming a symmetrical shape calculate the 10 year recurrence interval design storms for point rainfall appropriate for

(a) Nairobi

(b) Kampala

(c) Dar es Salaam

(a) Nairobi

Proceed as in example 1 (point marked 'N' on Appendix 1 Fig. 1).

From Appendix 1 Figs. 1, 2, 3	2 year 24 hour rainfall	= 70 mm
	2 year: 10 year ratio	= 1.60
	10 year flood factor	= 1.60
	10 year rainfall	= 112 mm

From Appendix 1 Table 1 'Zone 3' 'n' = 0.85

Using 'n' = 0.85 in Appendix 1 Fig. 5 calculate R_T for 15, 30 mins, 1 hr, 2 hr, 4 hr and plot as a symmetrical histogram in units of mm/15 mins.

15 mins	$0.25 \times 112\ R_T = 28.0$	$R_T = 28.0$
30 mins	$0.365 \times 112\ R_T = 40.9$	$R_T = 40.9 - 28.0 = 12.9$
1 hour	$0.485 \times 112\ R_T = 54.3$	$R_T = \frac{54.3 - 40.9}{2} = 6.7$
2 hour	$0.610 \times 112\ R_T = 68.3$	$R_T = \frac{68.3 - 54.3}{4} = 3.5$
4 hour	$0.720 \times 112\ R_T = 80.6$	$R_T = \frac{80.6 - 68.3}{8} = 1.5$

These values are shown plotted on Appendix 1 Fig. 6(b)

(b) Kampala

Proceed as in example 1 (point marked 'K' on Appendix 1 Fig. 1)

From Appendix 1 Figs. 1, 2, 3	2 year 24 hour rainfall	= 70 mm
	2 year:10 year ratio	= 1.49
	10 year flood factor	= 1.49
	10 year rainfall	= 104 mm

From Appendix 1 Table 1 Zone 1 'n' = 0.96

Using 'n' = 0.95 in Appendix 1 Fig. 5 calculate R_T for 15 min, 30 min, 1, 2, 4 hrs and plot as symmetrical histogram in units of mm/15 mins.

15 mins	$0.36 \times 104\, R_T = 37.4$	$R_T = 37.4$
30 mins	$0.51 \times 104\, R_T = 53.0$	$R_T = 53.0 - 37.4 = 15.6$
1 hour	$0.655 \times 104\, R_T = 68.1$	$R_T = \frac{68.1 - 53.0}{2} = 7.5$
2 hour	$0.825 \times 104\, R_T = 85.8$	$R_T = \frac{85.8 - 68.1}{4} = 4.4$
4 hour	$0.855 \times 104\, R_T = 88.9$	$R_T = \frac{88.9 - 85.8}{8} = 0.4$

These values are shown plotted on Appendix 1 Fig. 6 (e)

(c) Dar es Salaam

From Appendix 1 Figs. 1, 2, 3	2 year 24 hour rainfall	= 70-80 mm (say 75 mm)
	2 year: 10 year ratio	= 1.64
	10 year flood factor	= 1.64
	10 year rainfall	= 123 mm
From Appendix 1 Table 1 Zone 3 'n'		= 0.76

Using 'n' = 0.75 in Appendix 1 Fig. 5 calculate R_T for 15 min, 30 min, 1, 2, 4 hrs. and plot as symmetrical histogram in units of mm/15 mins.

15 mins	$0.170 \times 123\, R_T = 20.9$	$R_T = 20.9$
30 mins	$0.260 \times 123\, R_T = 32.0$	$R_T = 32.0 - 20.9 = 11.1$
1 hour	$0.365 \times 123\, R_T = 44.9$	$R_T = \frac{44.9 - 32.0}{2} = 6.5$
2 hour	$0.485 \times 123\, R_T = 59.7$	$R_T = \frac{59.7 - 44.9}{4} = 3.7$
4 hour	$0.610 \times 123\, R_T = 75.0$	$R_T = \frac{75.0 - 59.7}{8} = 0.5$

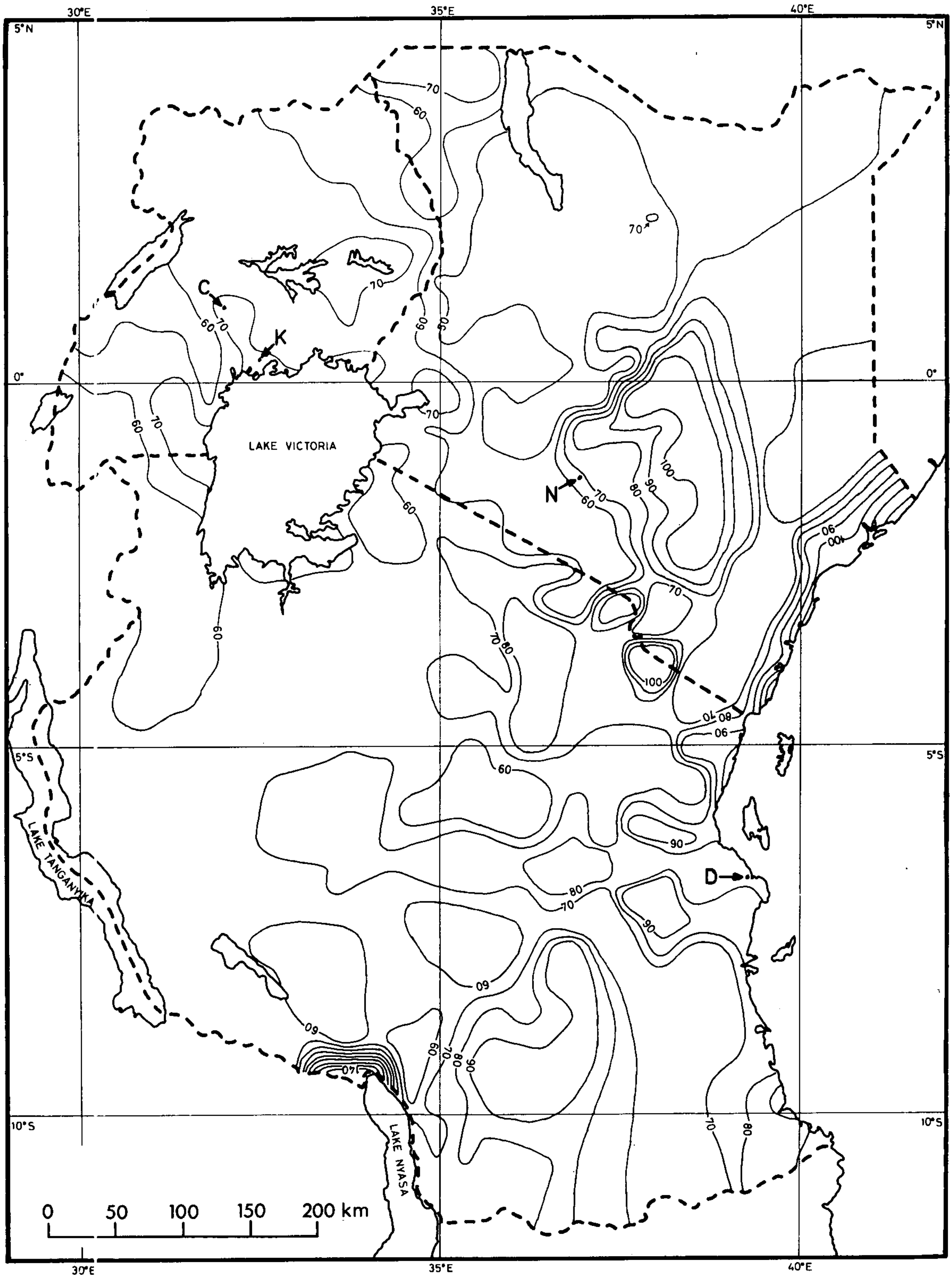
These values are shown plotted in Appendix 1 Fig. 6 (d).

APPENDIX 1

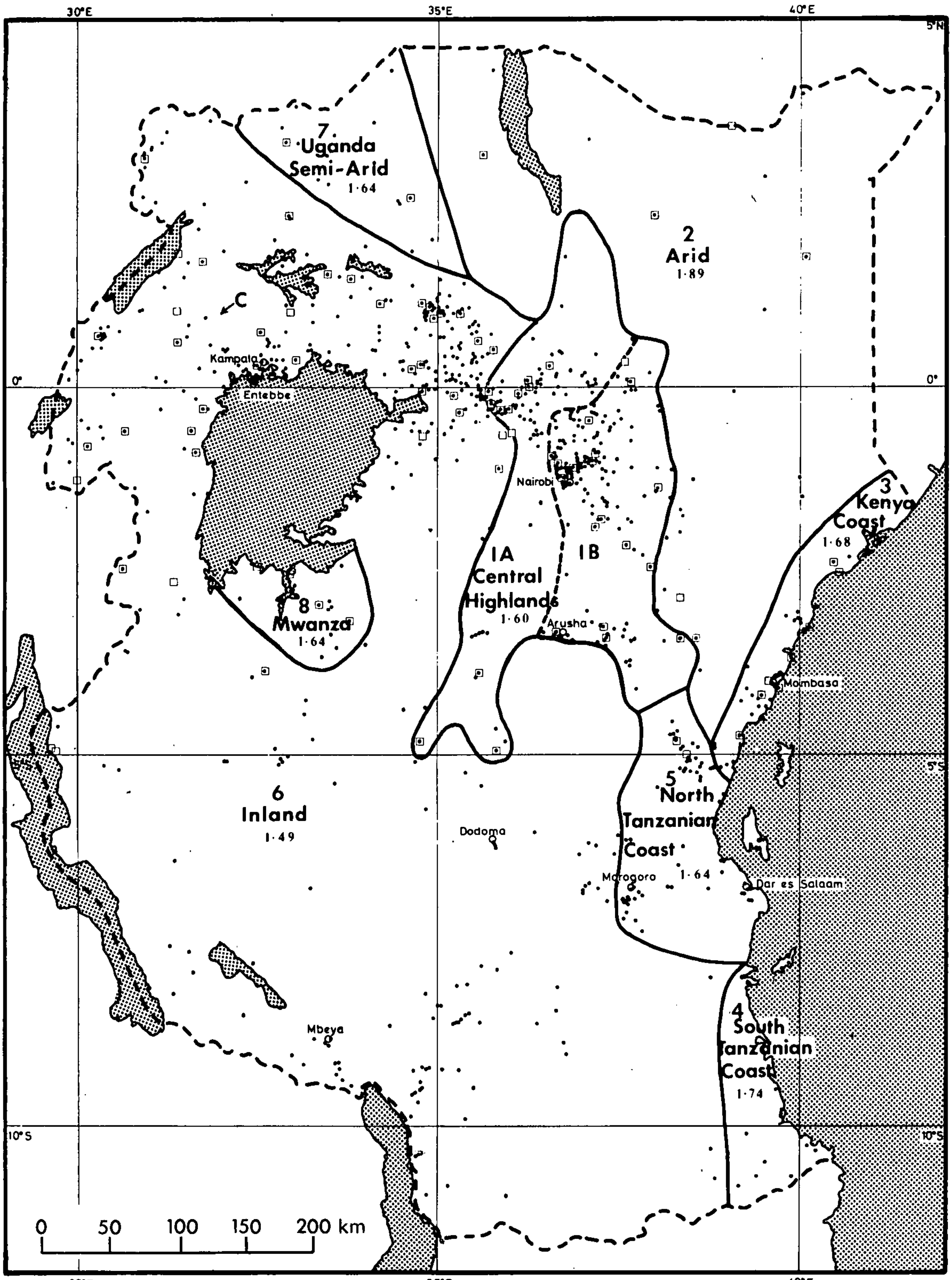
TABLE 1

Average values for the index 'n' in the equation $I = \dfrac{a}{(T+0.33)^n}$

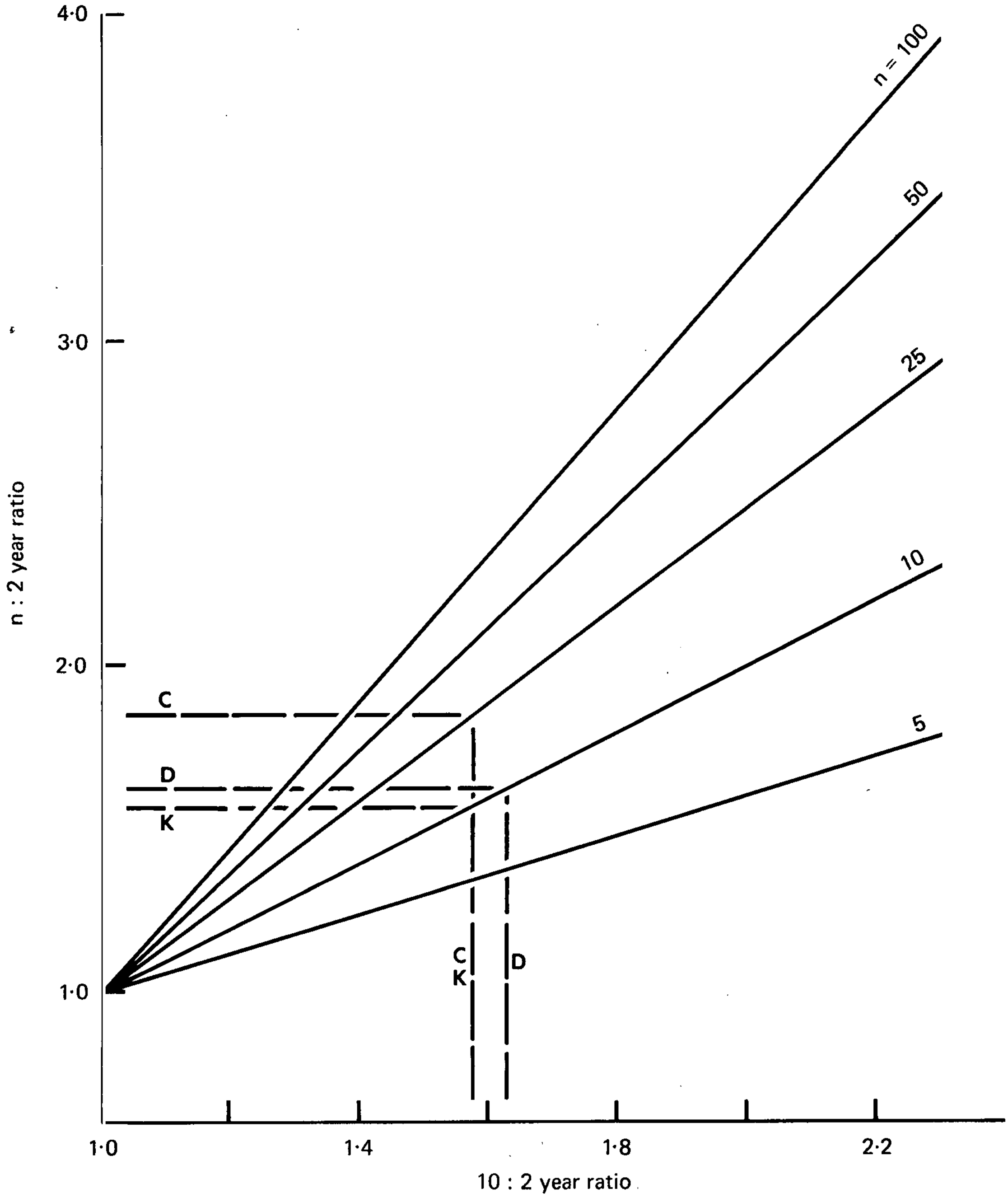
Zone	Recurrence Interval		
	2 year	5 year	10 year
1. Inland Stations	0.98	0.96	0.96
2. Coastal Stations	0.82	0.76	0.76
3. Eastern slopes of Kenya-Aberdare Range	0.82	0.85	0.85



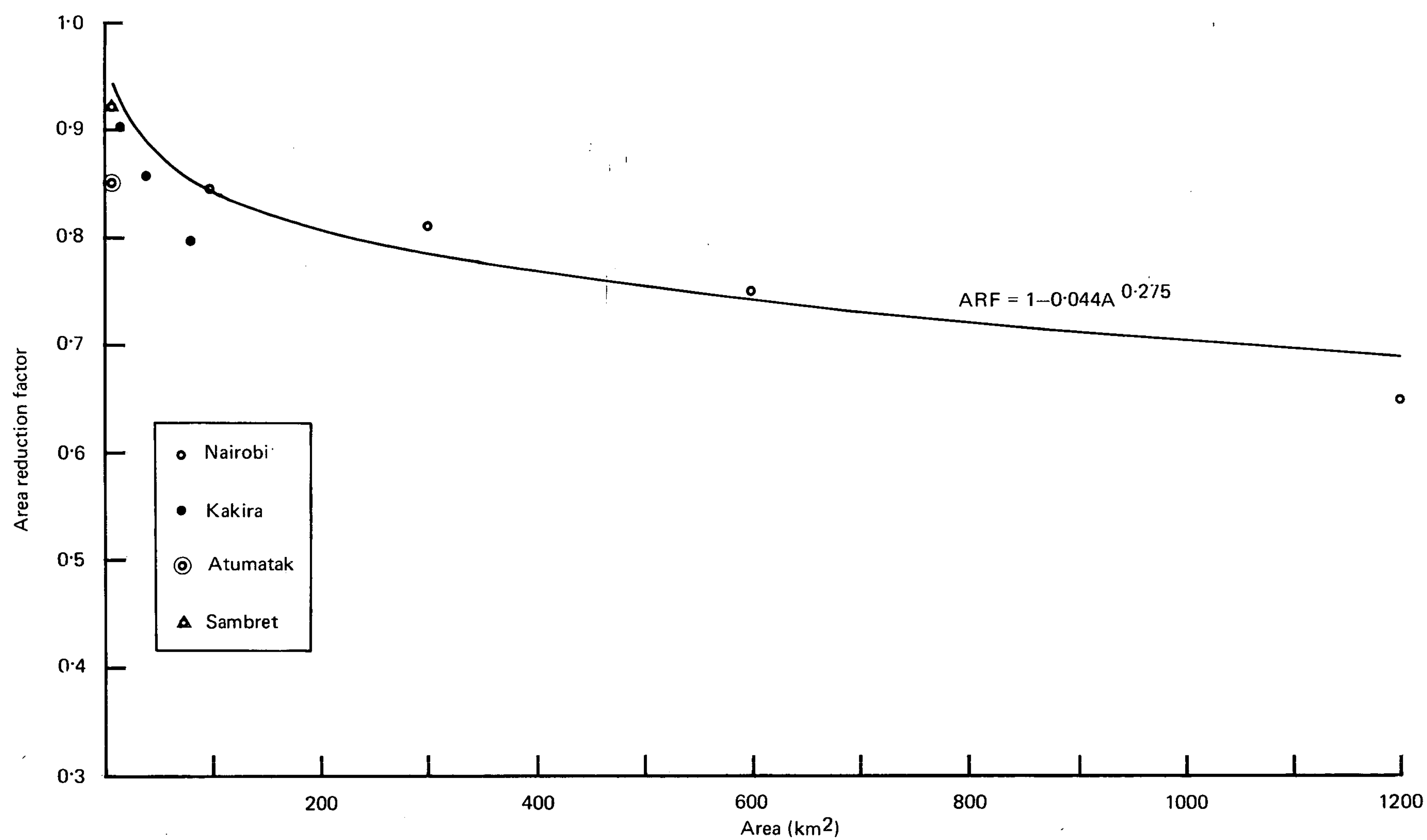
Appendix 1. Fig. 1. 2 YEAR 24 HOUR STORM RAINFALL (mm)



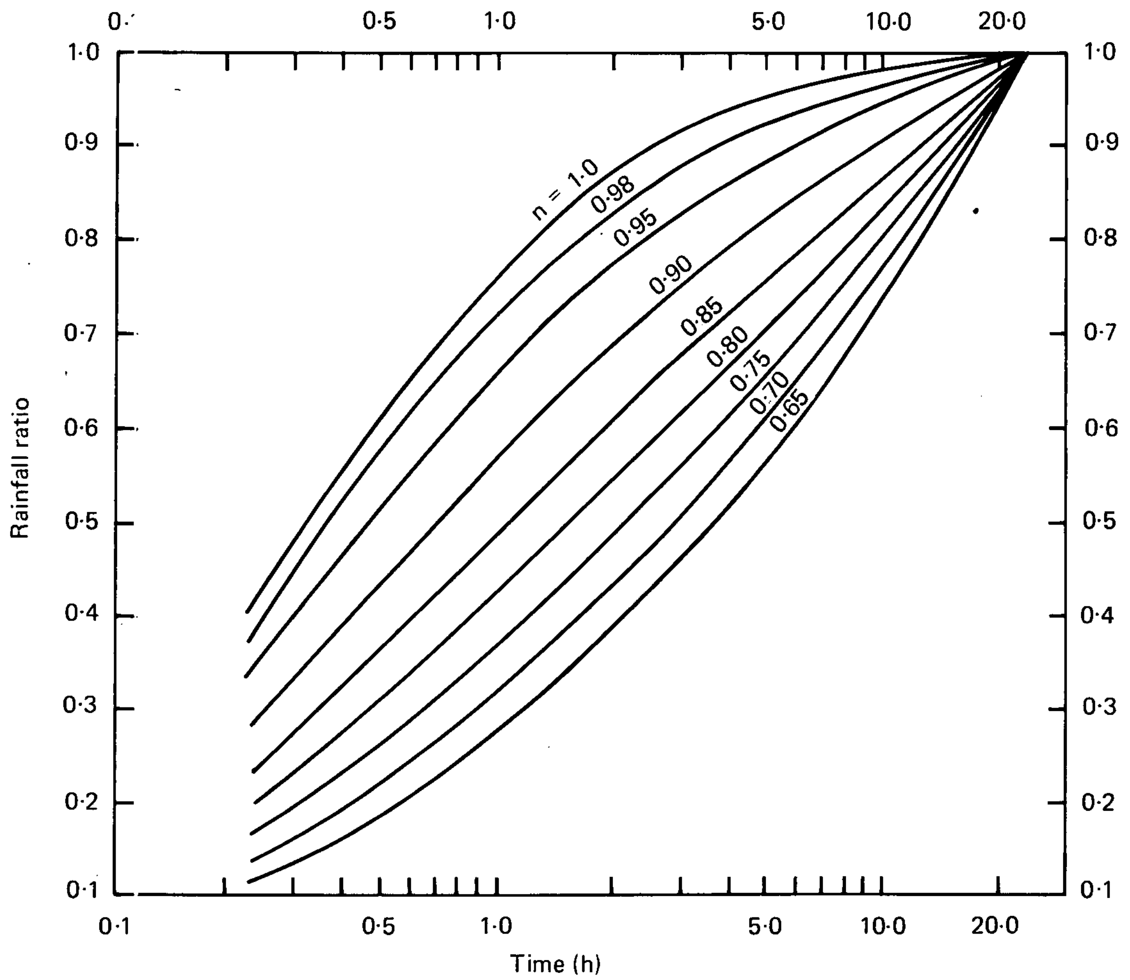
Appendix 1. Fig. 2. 10 YEAR : 2 YEAR RATIO



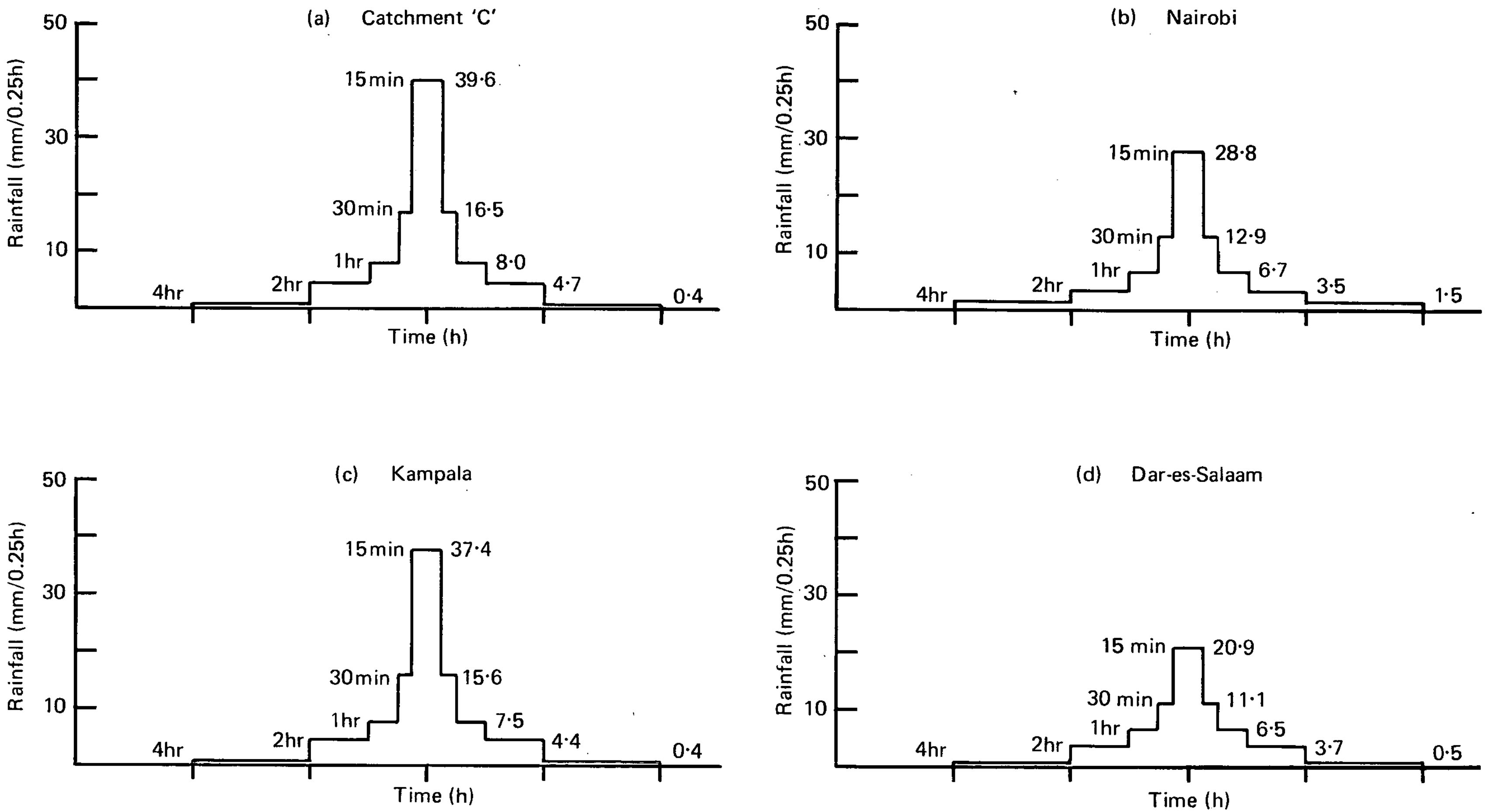
Appendix 1. Fig. 3 FLOOD FACTORS



Appendix 1. Fig. 4. EAST AFRICAN AREAL REDUCTION FACTORS



Appendix 1. Fig. 5. EAST AFRICAN RAINFALL RATIOS



Appendix 1. Fig. 6. DESIGN STORMS FOR 4 AREAS IN EAST AFRICA

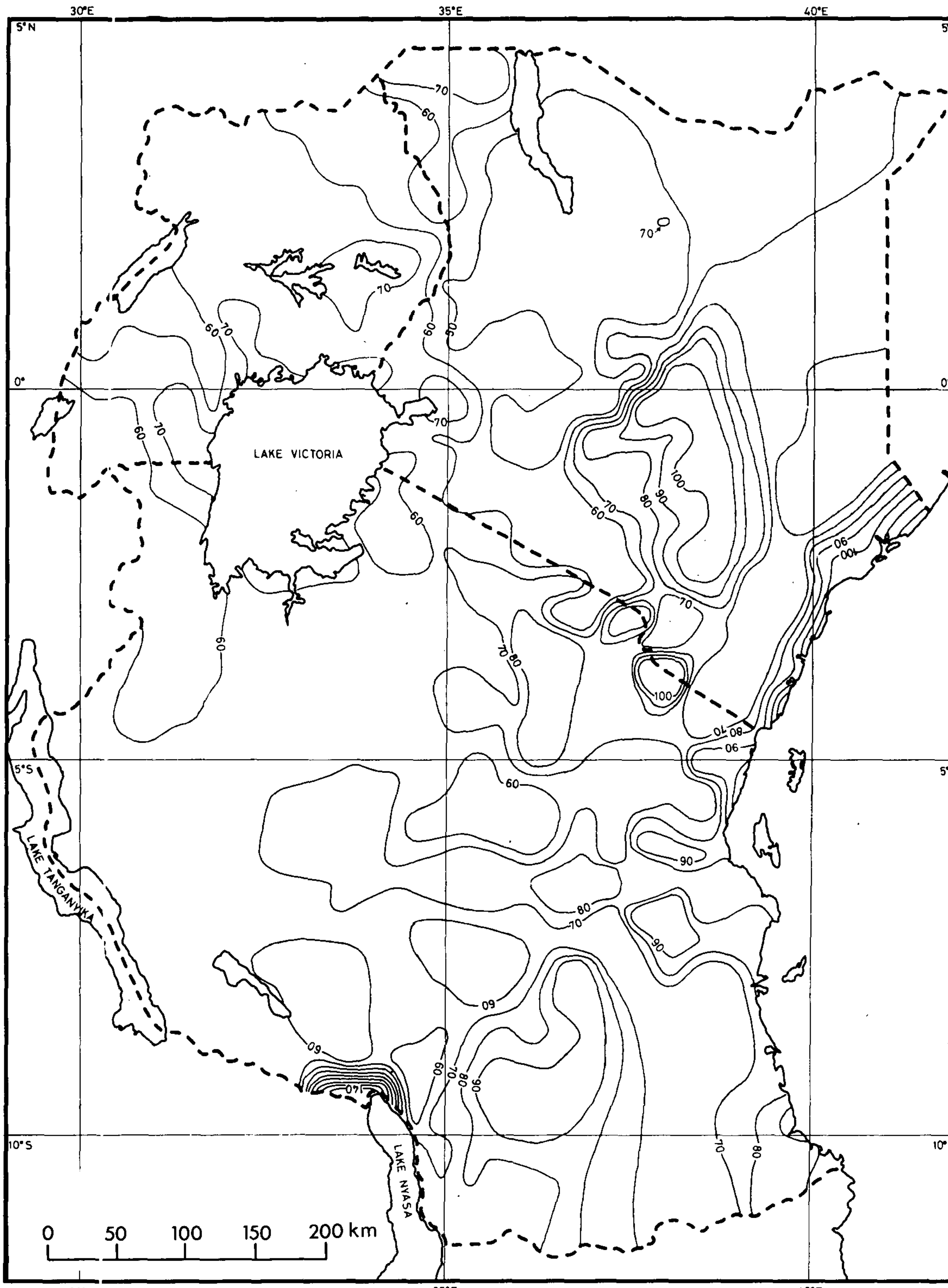


Fig. 1 2 YEAR 24 HOUR STORM RAINFALL (mm)

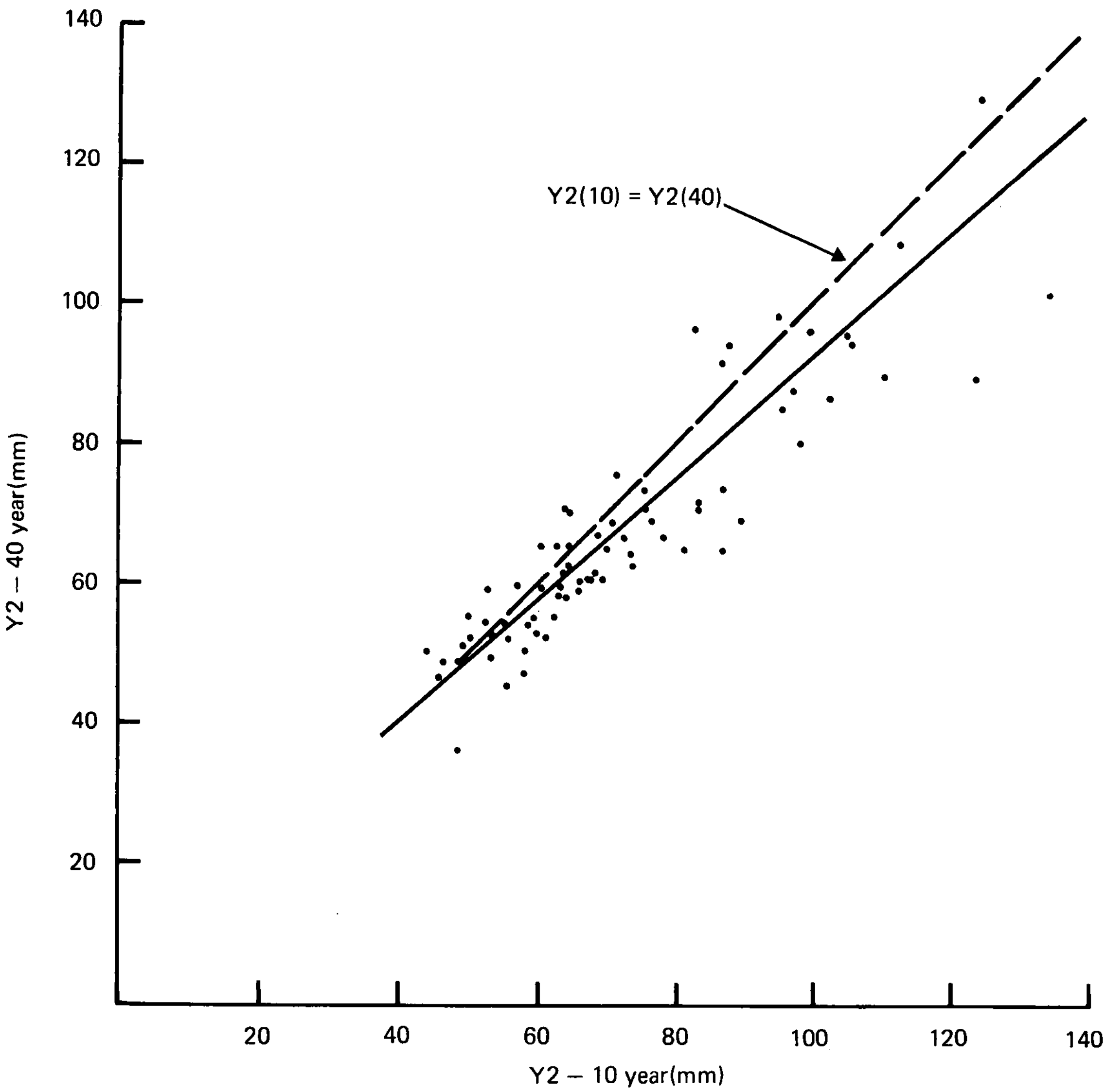


Fig. 2 COMPARISON OF 2 YEAR (mm) ESTIMATES OF STORM RAINFALL USING 10 YEAR AND 40 YEAR PERIODS OF RECORD

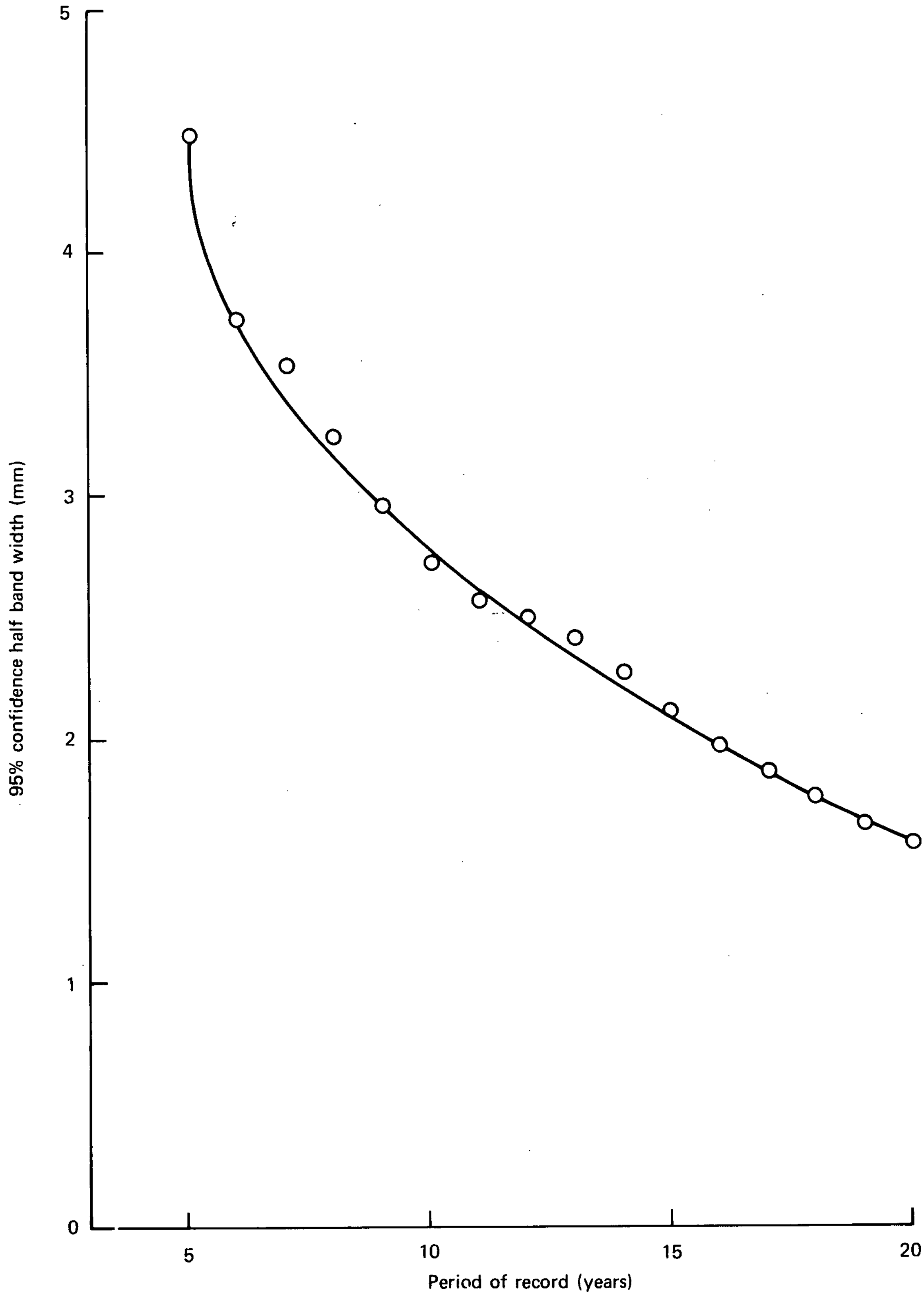


Fig. 3 95% CONFIDENCE LIMITS FOR RUNNING MEANS OF ANNUAL RAINFALL MAXIMA

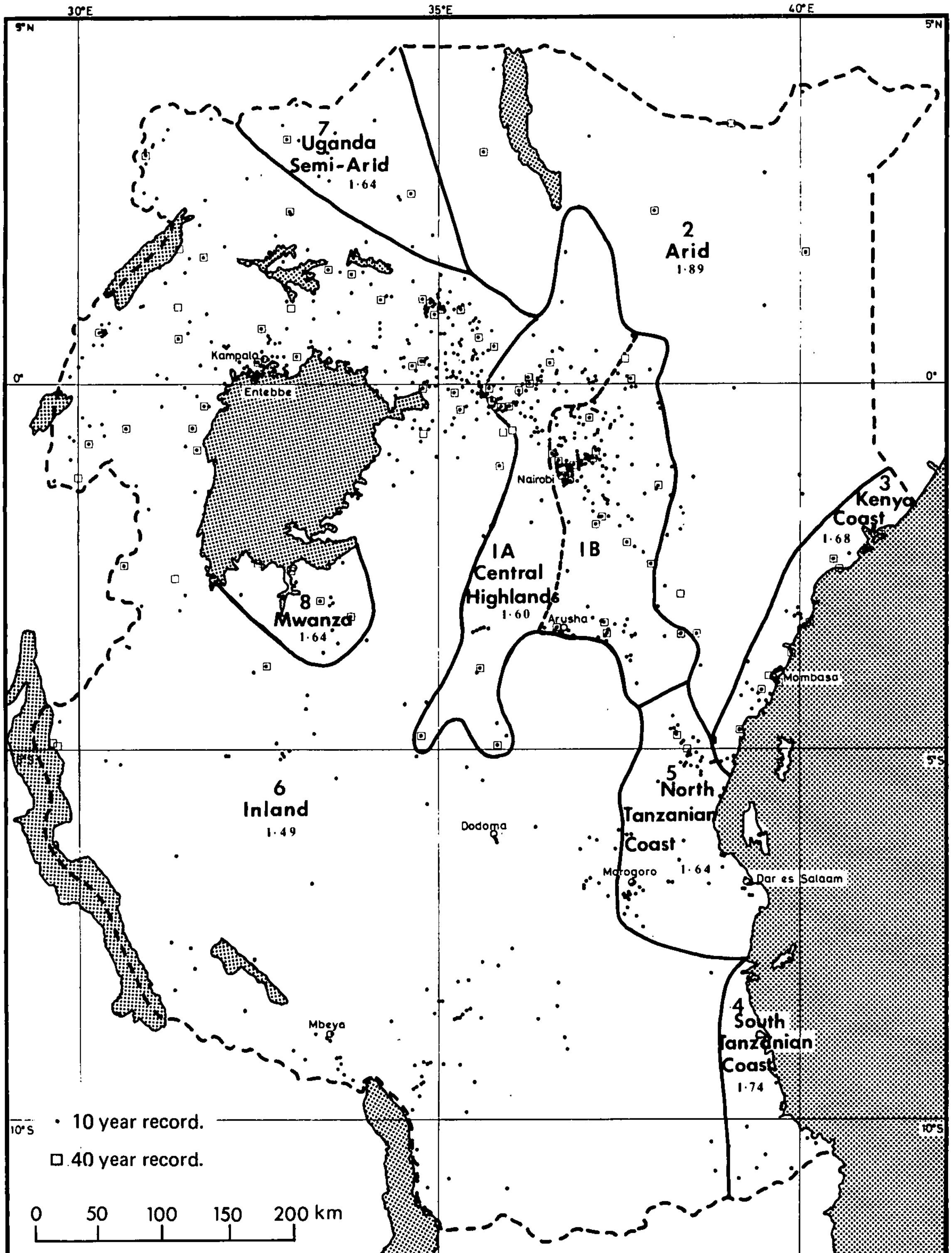


Fig. 4. 10 YEAR : 2 YEAR RATIO

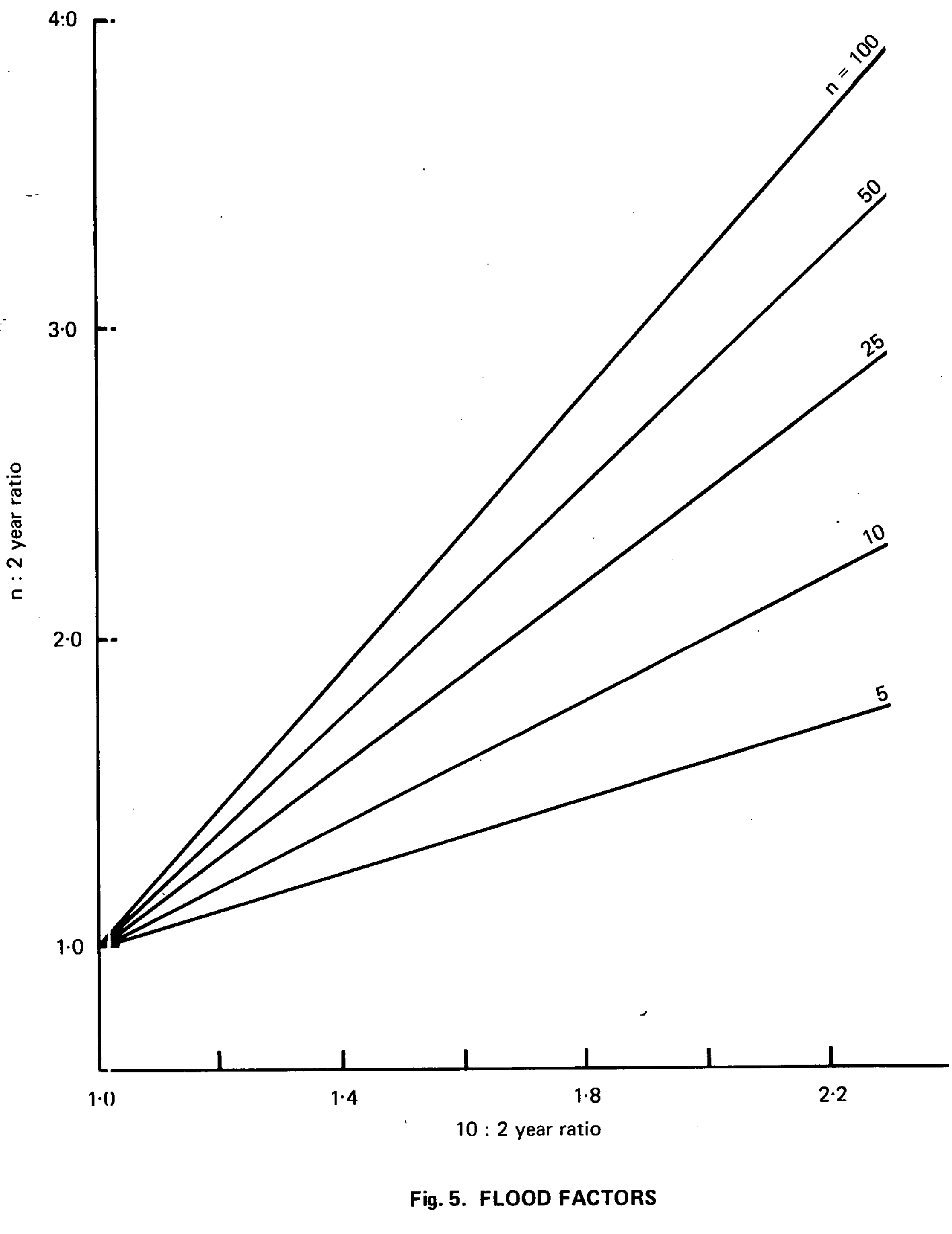


Fig. 5. FLOOD FACTORS

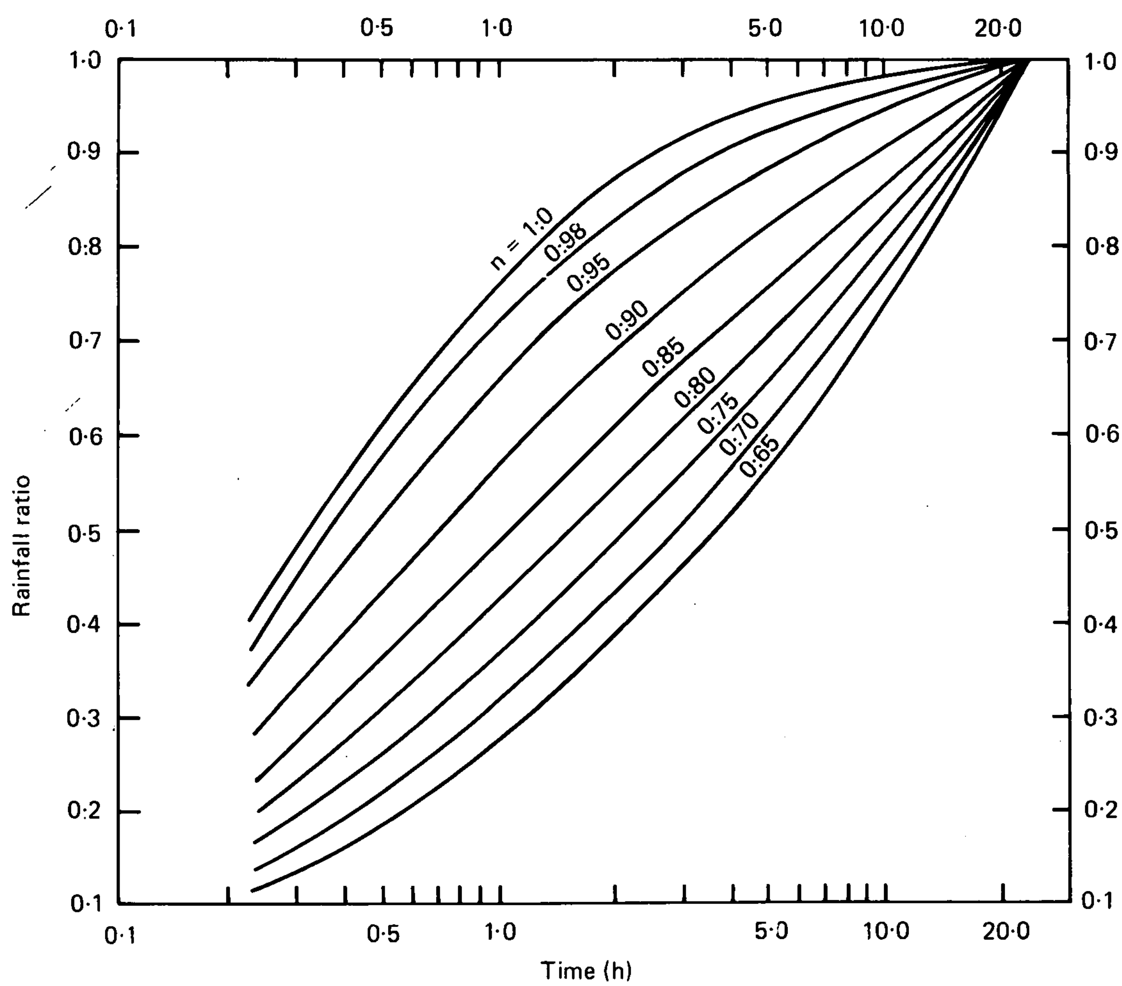


Fig. 6 EAST AFRICAN RAINFALL RATIOS

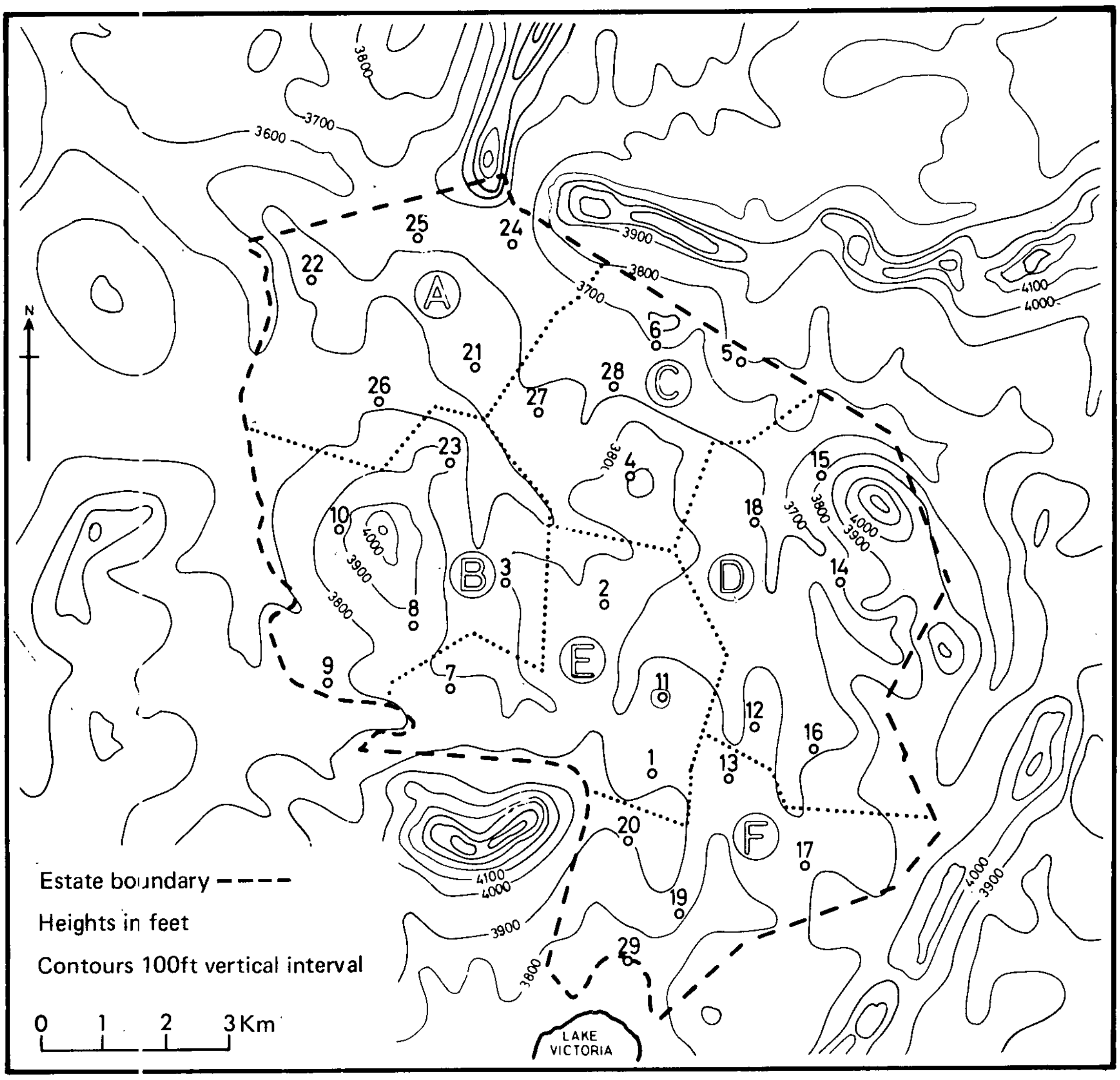


Fig. 7. KAKIRA RAINGAUGE NETWORK

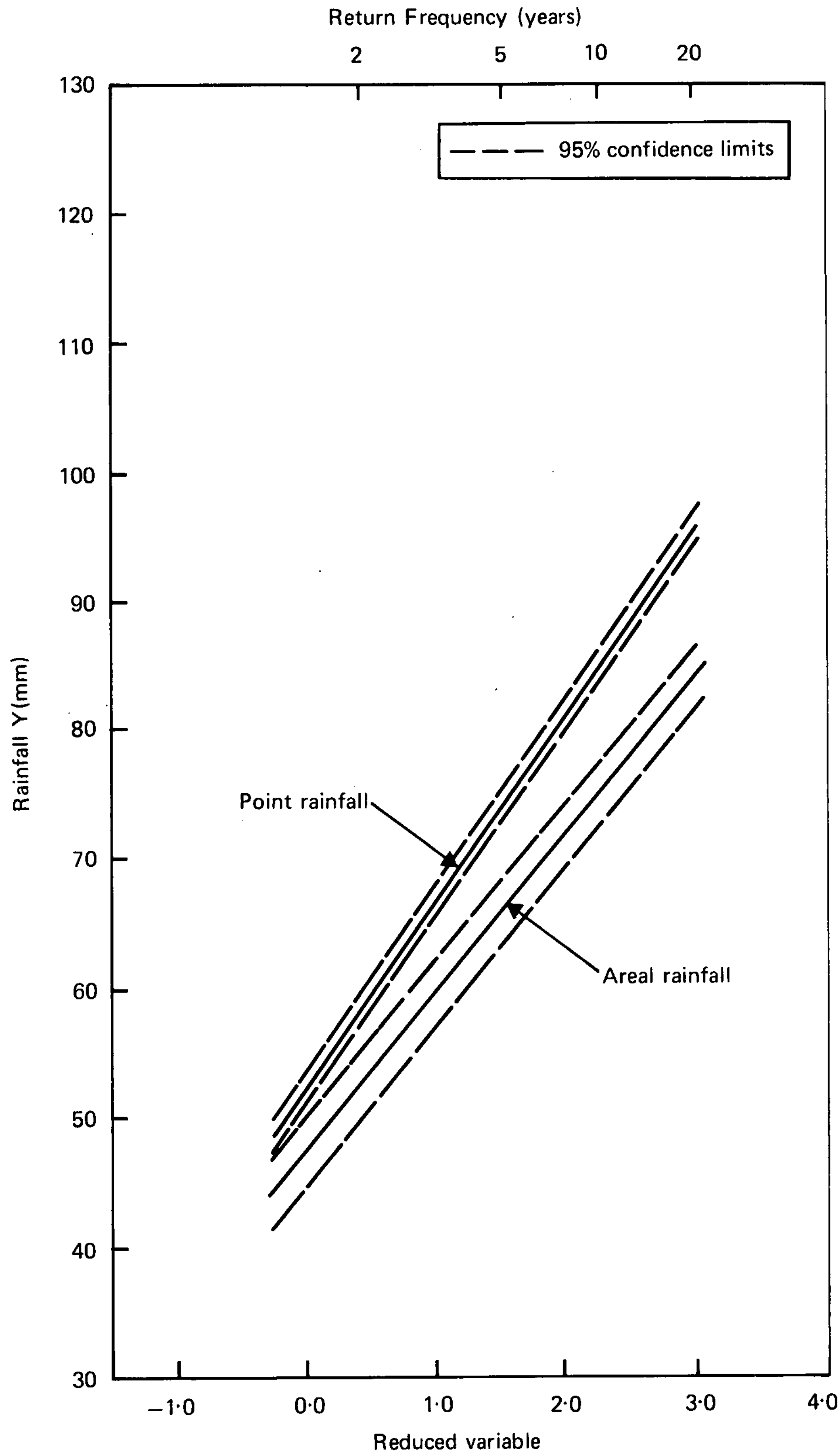


Fig. 8 COMPARISON OF AREAL AND POINT DAILY RAINFALL – FREQUENCY RELATIONSHIPS FOR AN AREA OF 15 km^2

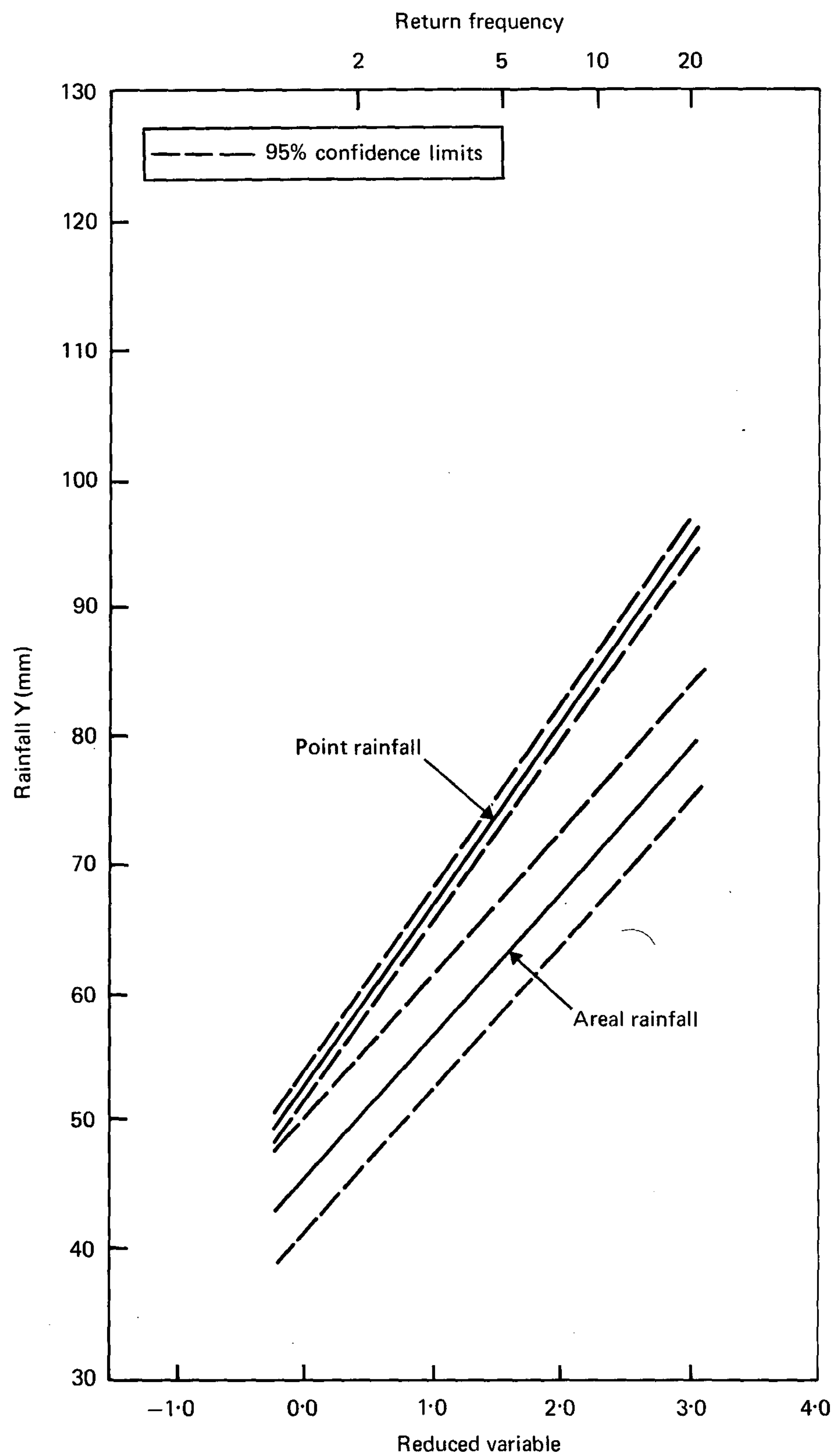


Fig. 9. COMPARISON OF AREAL AND POINT DAILY RAINFALL – FREQUENCY RELATIONSHIPS FOR AN AREA OF 40 km^2

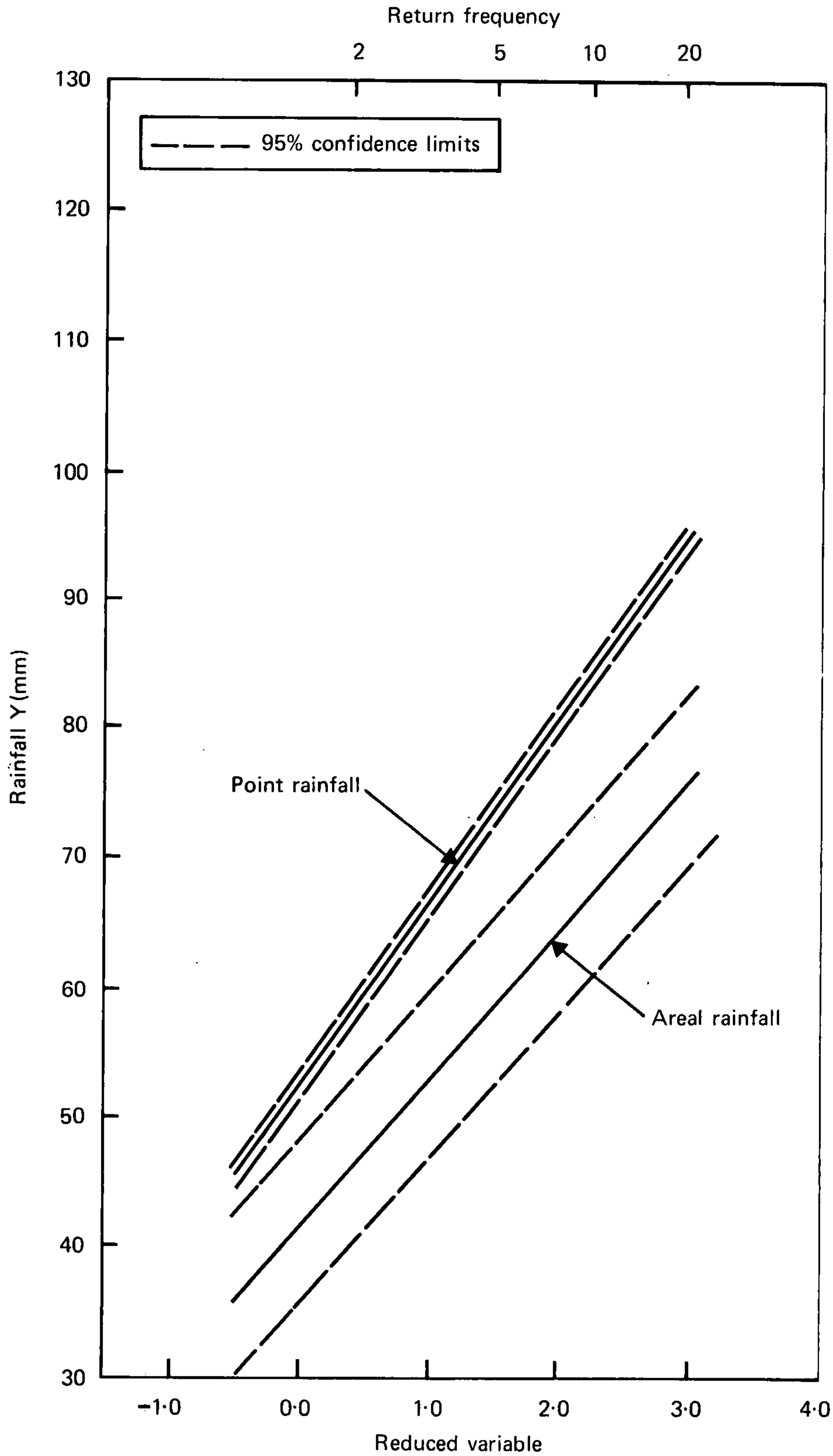


Fig. 10 COMPARISON OF AREAL AND POINT DAILY RAINFALL – FREQUENCY RELATIONSHIPS FOR AN AREA OF 80 km²

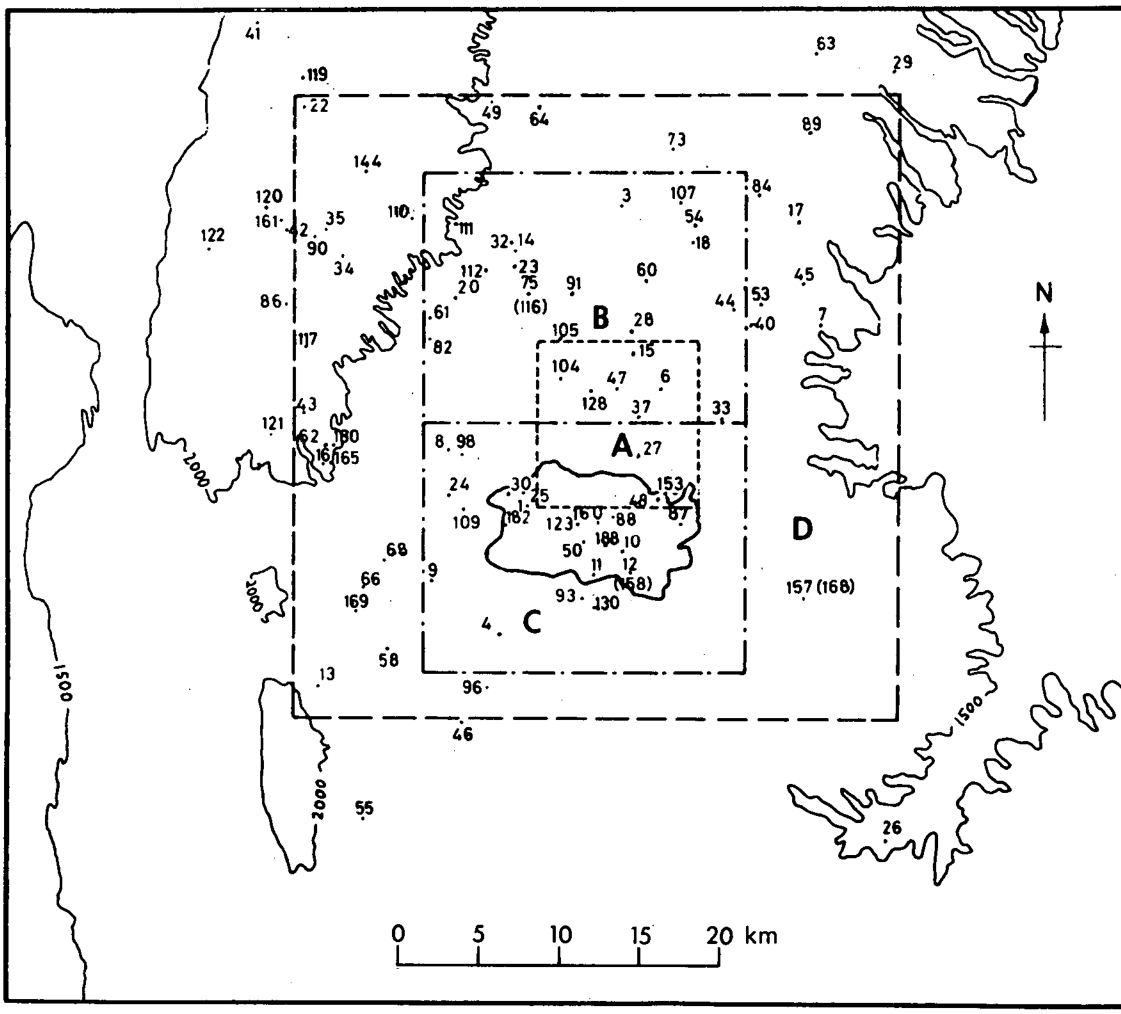


Fig. 11 NAIROBI RAINGAUGE NETWORK & SUBAREAS

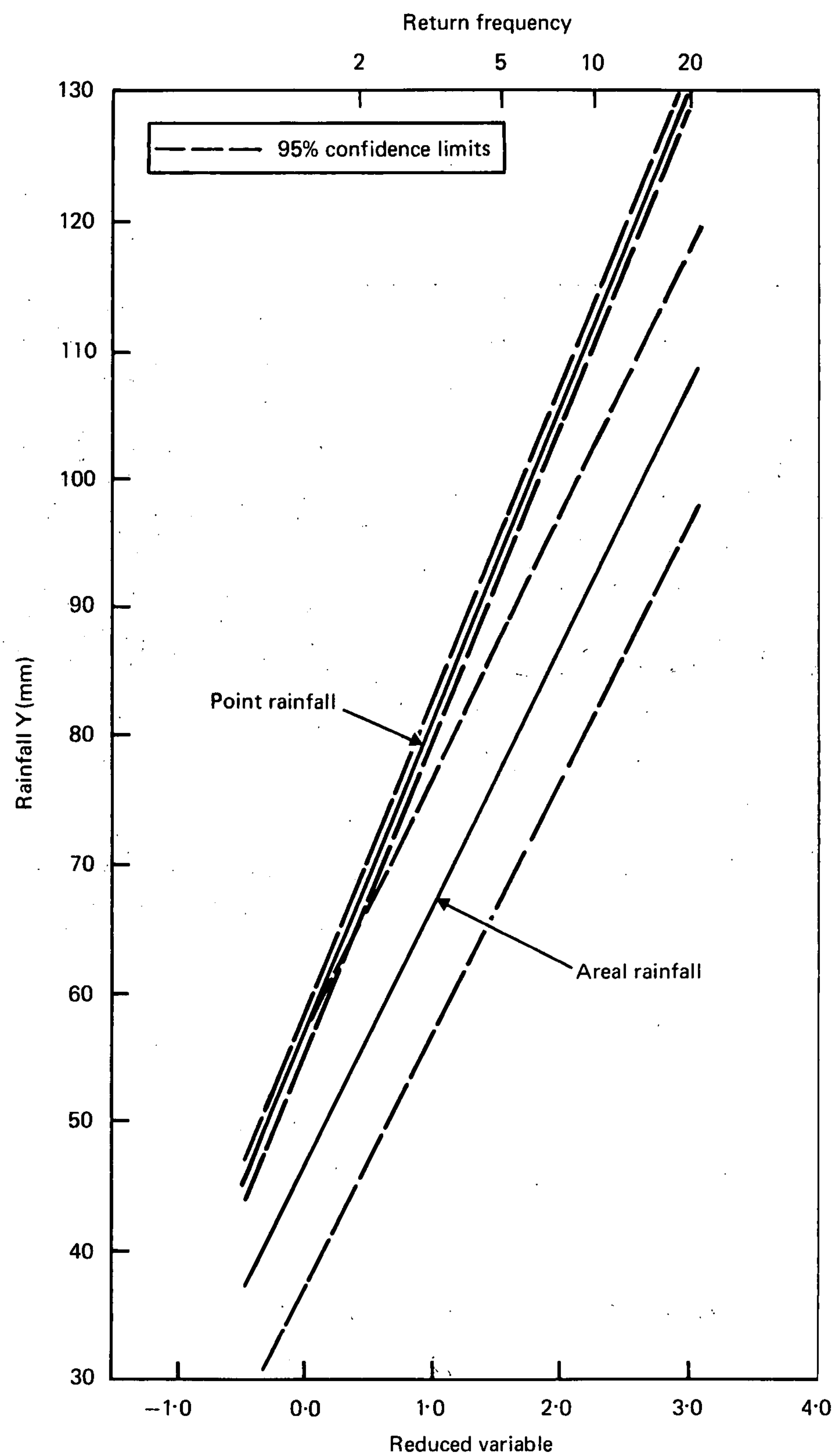


Fig. 12 COMPARISON OF AREAL AND POINT DAILY RAINFALL – FREQUENCY RELATIONSHIPS FOR AN AREA OF 100 km^2

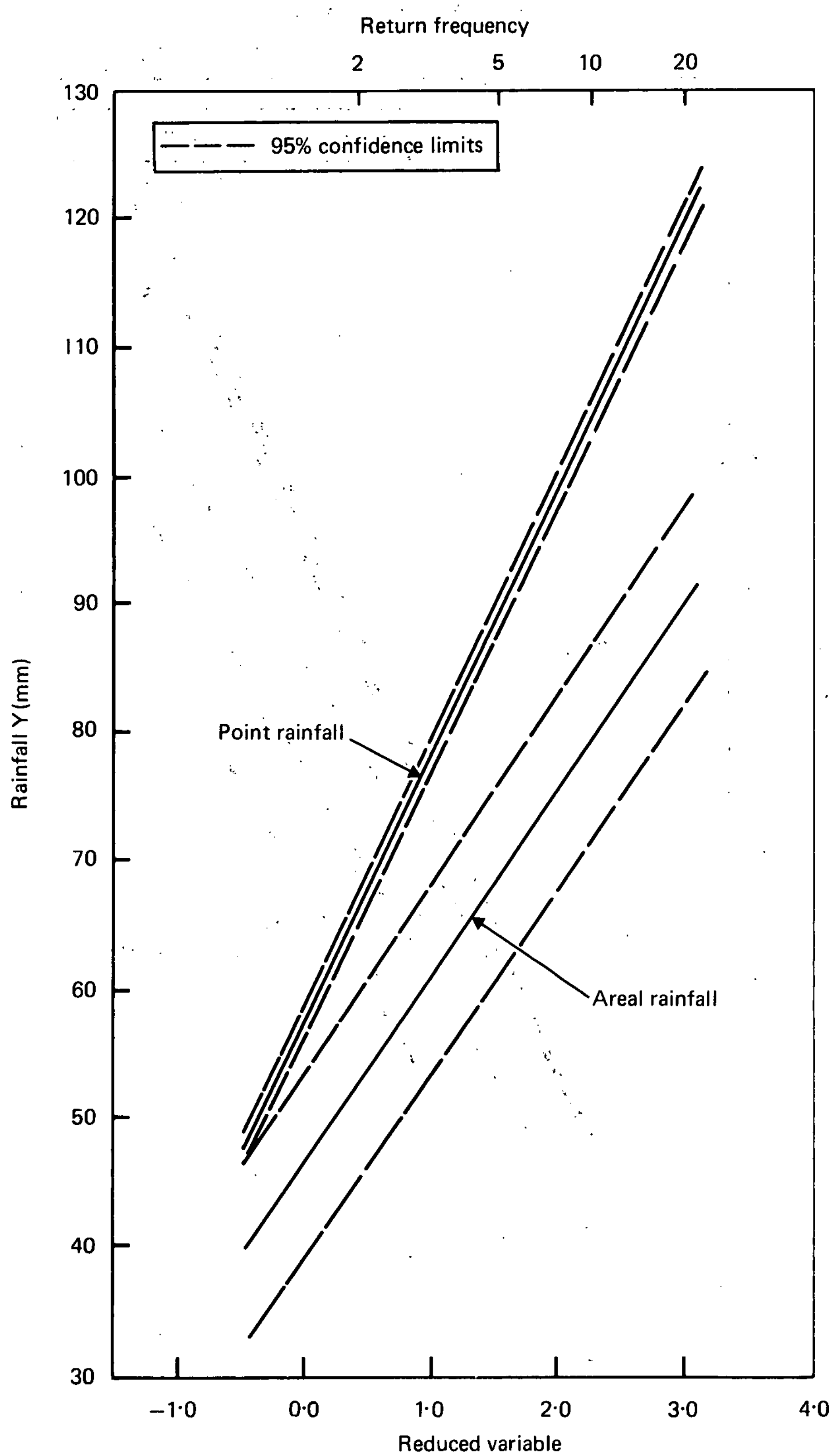


Fig. 13. COMPARISON OF AREAL AND POINT DAILY RAINFALL – FREQUENCY RELATIONSHIPS FOR AN AREA OF 300 km^2

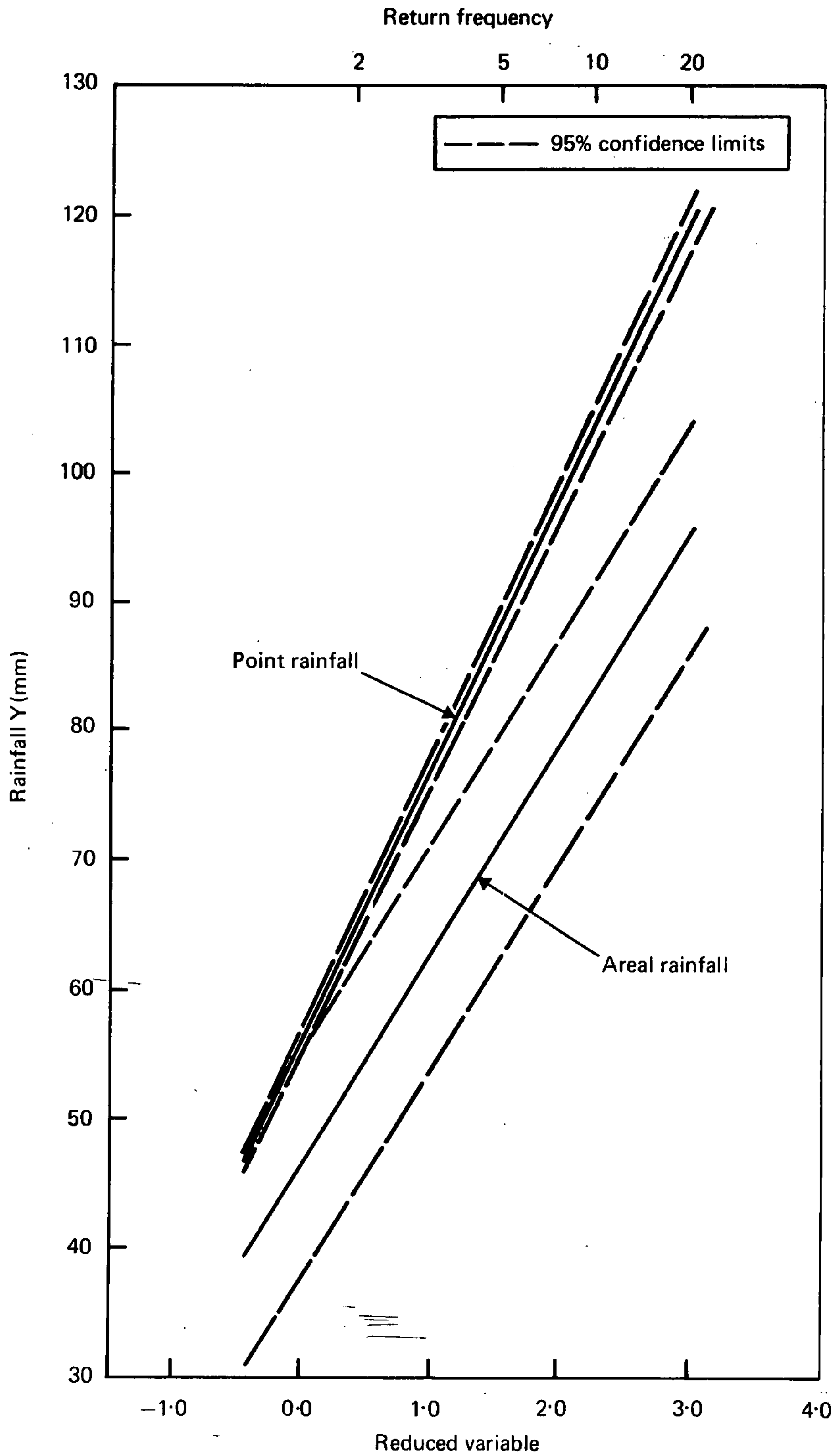


Fig. 14 COMPARISON OF AREAL AND POINT DAILY RAINFALL – FREQUENCY RELATIONSHIPS FOR AN AREA OF 300 km²

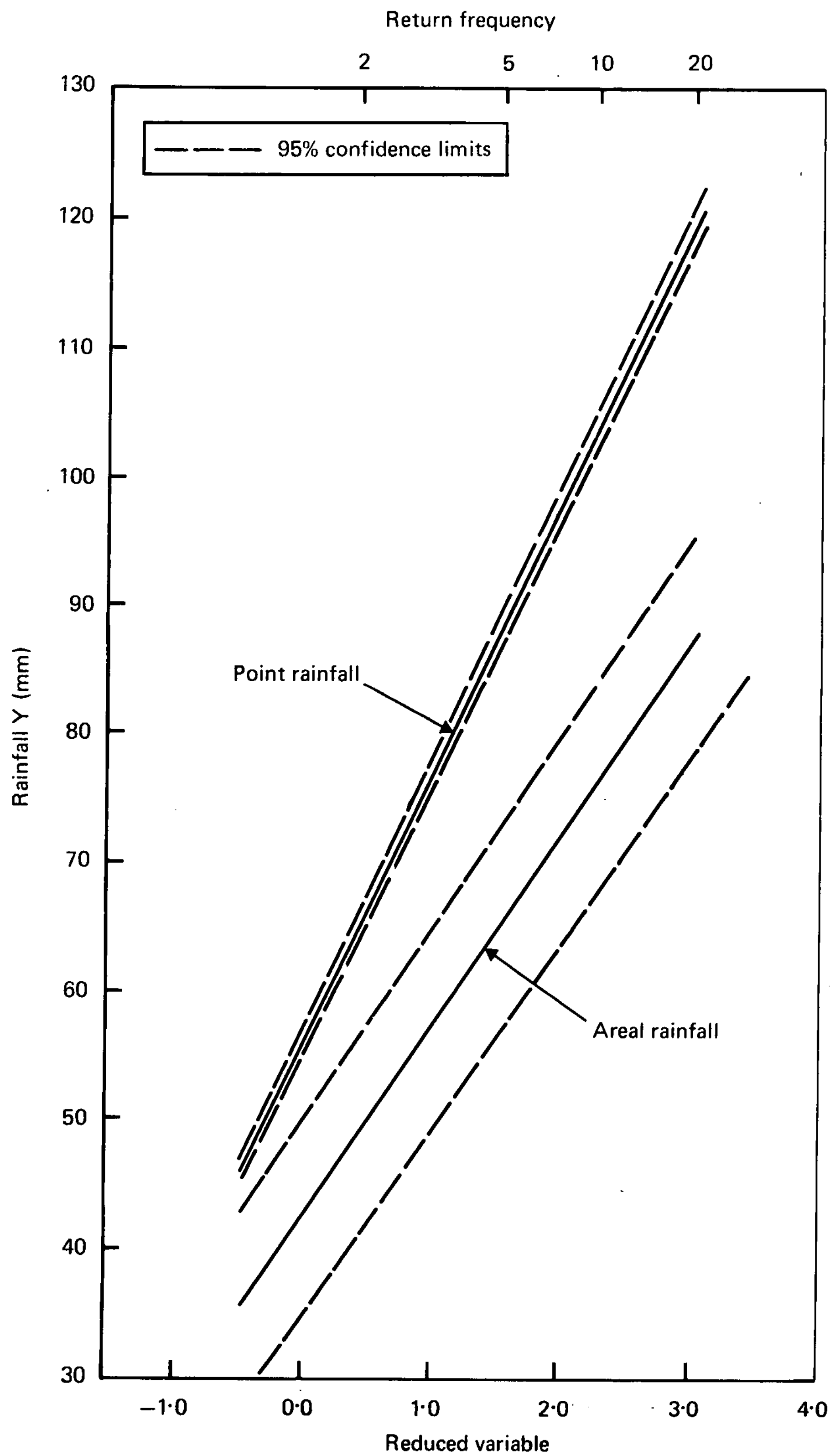


Fig. 15 COMPARISON OF AREAL AND POINT DAILY RAINFALL – FREQUENCY RELATIONSHIPS FOR AN AREA OF 600 km²

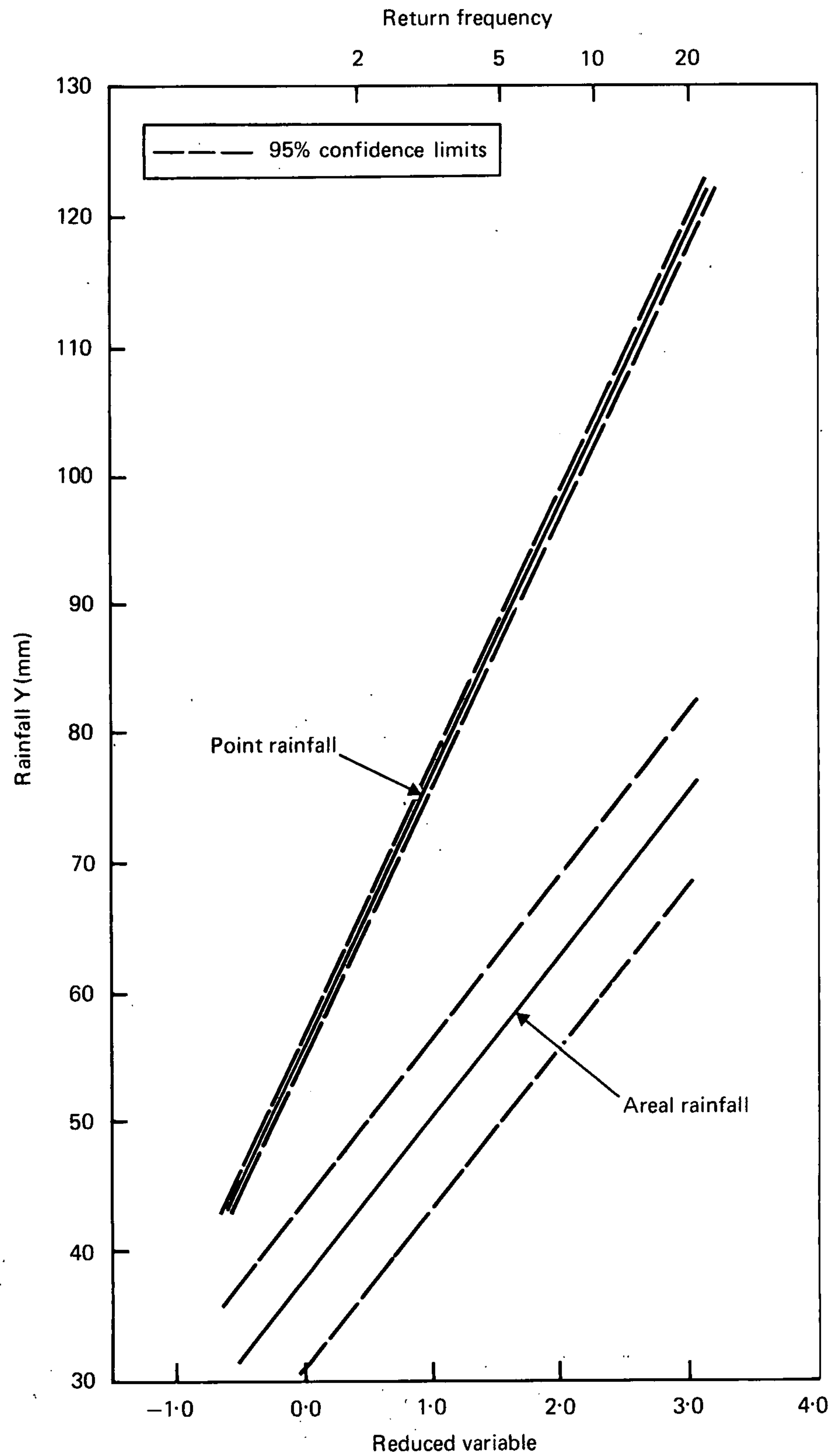


Fig. 16. COMPARISON OF AREAL AND POINT DAILY RAINFALL FREQUENCY RELATIONSHIPS FOR AN AREA OF 1200 km^2

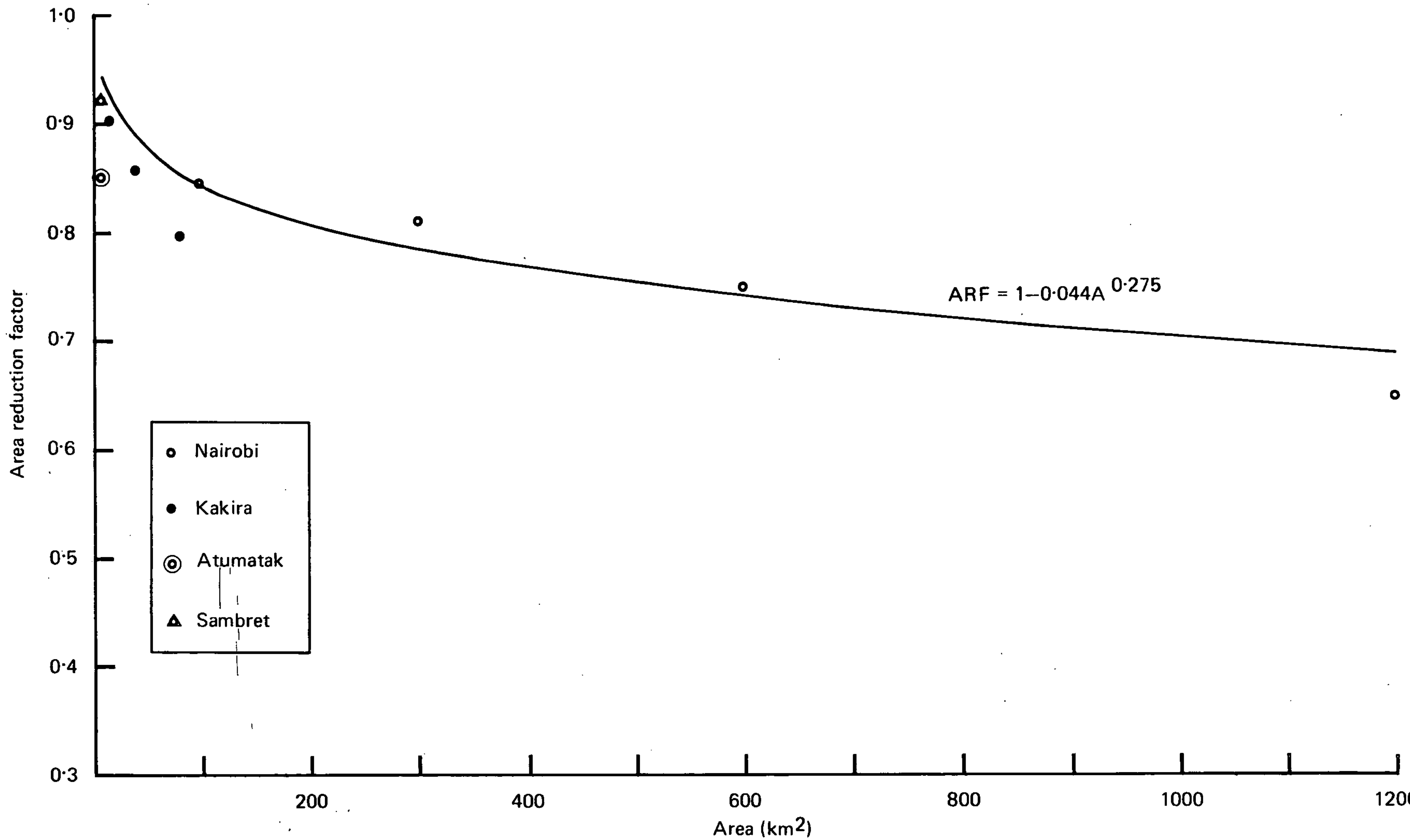


Fig. 17. EAST AFRICAN AREAL REDUCTION FACTORS

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ABSTRACT

The predicting of storm rainfall in East Africa: D. FIDDES, B.Sc., M.Sc., C.Eng., M.I.C.E., DIC., J. A. FORSGATE, B.Sc., and A. O. GRIGG: Department of the Environment, TRRL Laboratory Report 623: Crowthorne, 1974 (Transport and Road Research Laboratory). A simple method for predicting the characteristics of storms for the design of drainage structures in East Africa is described. The variation of 2 year daily point rainfall, and the 10:2 year ratio for daily rainfall, over East Africa are given in map form. Using these, daily point rainfall for any return frequency can be calculated. To arrive at the design storm the daily point rainfall is adjusted using a generalised depth-duration equation and a graphical representation of the variation of mean rainfall with area.

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