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Natural Environment Research Council

Regional Rainfall Frequency South West England

A Report to South West Water

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Contents

REGIONAL RAINFALL FREQUENCY - SOUTH WEST ENGLAND

1. Introduction

The analysis of rainfall frequency is fundamental to reservoir safety assessment. This report presents a detailed study of the frequency of 1 and 2-day rainfalls in South West England. Particular emphasis is placed on the analysis of rainfall depth-frequency relationships for Wimbleball Reservoir, in order to derive estimates of design rainfalls of up to 10,000-year return period.

The report discusses the background to the problem of rainfall frequency estimation in South West England and outlines the methodology adopted in the analysis. Details of the mapping of two key rainfall statistics are given, and growth curves centred on ten locations within the study region are presented.

2. The problem of rainfall frequency in South West England

UK practice in the estimation of rainfall frequency relies on the method presented in Volume II of the Flood Studies Report (Natural Environment Research Council, 1975). The approach taken is a two-stage one, involving the estimation of the rainfall of 5-year return period (M5) to which a growth factor is applied to yield the rainfall of the required duration and return period. Two geographical regions, England & Wales and Scotland & Northern Ireland, are distinguished, across each of which a fixed set of growth factors is assumed.

In an analysis of 2-day rainfall using a number of long-term gauge records in Somerset, Bootman & Willis (1977 & 1981) expressed concern about the applicability of the FSR II growth factors to South West England. It was demonstrated that the FSR method seriously underestimates the frequency of 2-day rainfalls in the region.

More recently, the derivation of regional growth curves for 1-day rainfall (Reed & Dales, 1988) has confirmed strong regional traits within the UK which are not represented in the FSR II growth factors. An alternative generalization of point rainfall frequency has been proposed, based on the regions shown in Fig. 1. It was noted that the West Country region exhibited particularly high values of the coefficient of variation (CV) of 1-day annual maximum rainfall at a number of gauges. Historically, the region has experienced a relatively high frequency of heavy rainfall events, often associated with summer thunderstorms.

In the light of these apparent anomalies in the FSR II model, the availability of long and short-term daily raingauge data in the region has allowed a detailed re-evaluation of rainfall frequency in South West England.

3. Study region

Wimbleball Reservoir is situated in the South West region presented in Reed & Dales (1988), close to the boundary of the West Country region and the area of Somerset for which the FSR method is known to underestimate rainfall frequency (Fig.1). For these reasons, the study region was defined as the area represented by the combined South West and West Country regions.

4. The analytical approach

The two-stage approach to the development of rainfall frequency relationships has been retained in the study. However, at the first stage, the mean annual maximum rainfall (RBAR) of the appropriate duration has been used as the standardizing variable, in preference to the M5 rainfall value. This follows the method adopted by Reed & Dales (1988) in order to correct for regional discrepancies in the FSR model. The advantages of using RBAR are its simplicity and the fact that it avoids a distributional assumption.

The second stage of the analysis has been concerned with the development of 1 and 2-day rainfall growth curves for South West England. A new technique for rainfall growth estimation has been developed which provides a more detailed regionalization than the FSR method, yet avoids imposing regional boundaries.

5. Mapping of rainfall statistics

5.1 THE REQUIREMENT

Detailed maps of 1 and 2-day RBAR values for South West England were required as the first stage of the procedure for deriving point rainfall estimates of any return period. The rainfall regions of Reed & Dales (1988) were determined through the analysis of a second rainfall statistic, the coefficient of variation of 1-day rainfall (CV). Since CV is considered to be a useful measure of the variability of rainfall, maps of 1 and 2-day CV have also been produced.

5.2 AVAILABLE DATA

Several sources of long and short-term daily raingauge data were used for the mapping of RBAR and CV. The Institute of Hydrology holds daily rainfall totals from 1961 to the present for over 4000 gauges in the UK. A selected number of records of length greater than 40 years are also held. Additional long and short-term data were provided by South West Water.

Series of annual maximum 1 and 2-day rainfalls were extracted for each gauge situated within the study region. Maximum values were only accepted if three-quarters of the year's daily totals were available. At each gauge which could provide ten or more maxima, values of RBAR and CV were calculated. The numbers of gauges used in the mapping of RBAR and CV and their record lengths are shown in Table 1.

Table 1 Summary of daily gauge data used in the study

Number of years of record	Number of gauges
10 - 19	295
20 - 29	190
30 - 39	37
40 - 59	31
>60	37
Total	590

The raingauges are fairly evenly distributed and their positions are shown in Fig. 2. Point values of 1 and 2-day RBAR and CV are given in Appendix 1.

5.3 GEOSTATISTICAL ANALYSIS

5.3.1 Background to geostatistics

The method adopted in the mapping of the rainfall statistics is that of kriging, which is one of a number of techniques which comes under the general term geostatistics. Geostatistical techniques provide a set of statistical procedures for analysing the spatial structure of random variables and for performing interpolation and areal estimation (Cooper & Istok, 1988). These techniques have been used for some time in the field of mining and geology. More recently geostatistics have been applied to hydrological problem-solving (Delhomme, 1978), particularly in hydrogeology. However, a number of studies have been specifically concerned with the spatial variability of rainfall fields (Bastin *et al.*, 1984; Obled, 1987; Lebel & Laborde, 1988).

A primary advantage of geostatistical techniques is that they can be applied to irregular fields and are tolerant of missing values. Also, their theoretical basis does not take into account the physical nature of the phenomenon being studied, and when interpolation is carried out a measure of the estimation error is given. While the end-product of a geostatistical analysis is often a contour map of the required variable, a description of the nature of the spatial structure of the variable is also produced. Geostatistics therefore provide a powerful methodology for the analysis of point rainfall statistics which are irregularly distributed in space.

The geostatistical approach to mapping can be divided into three stages: description of the spatial correlation of a particular variable, modelling of the spatial structure of that variable and interpolation. The descriptive stage is based on the analysis of experimental semivariograms. A semivariogram expresses the spatial variability of an irregular field in terms of intersite distance; the mean spatial correlation between pairs of observations is plotted at regular distance intervals. The semivariogram generally increases with distance until it becomes approximately equal to the global variance in the field of values. Several semivariograms can be calculated for different directions in order to determine whether the spatial correlation function is isotropic. The second stage of the analysis involves fitting a mathematical model to the semivariogram. Finally, this model is used in kriging to obtain estimates of the variable of interest at unmeasured points.

Valid application of geostatistical techniques relies on certain conditions being met. The first assumption made is that the underlying distribution of the data points is normal. However, deviations from normality can often be corrected by transforming the data, for example by taking the natural logarithm of the observations. The regionalized variable is also assumed to be stationary.

5.3.2 Semivariogram analysis

Semivariograms were derived for 1 and 2-day RBAR and CV (Fig. 3). Firstly the data were checked for normality using the Kolmogorov-Smirnov statistic (Hoel, 1962). In each case it was found that taking the natural log transformation of the data increased the normality and following Rendu (1979) and Cooper & Istok (1988), a constant was added to improve the fit. The transformation used is given by

$$Y(x) = \ln [Z(x) + A] \quad (1)$$

where Y(x) is the natural log-transformed variable, Z(x) is the set of observations and A is a constant. Values of A are given in Table 2.

Table 2 Values of A used to improve the lognormal fit of the data points

Variable	A
1-day RBAR	-28.37
2-day RBAR	-26.33
1-day CV	20.75
2-day CV	7.24

Journel & Huijbregts (1978) give practical rules for estimating a true semivariogram from experimental data. They state that the number of sample pairs should be large, and that the semivariogram should not be estimated over a distance exceeding half the longest dimension of the region of study. Since 590 sample observations of RBAR and CV were available the first rule was easily met, and in accordance with the second, semivariograms were estimated over a maximum distance of 150 km.

Semivariograms in four directions were calculated for each variable and analysed using the UNIRAS graphics package (version 5.4). In each case, the forms of the semivariograms were similar in all directions. Therefore an isotropic semivariogram was derived for each variable and these are shown in Fig. 3.

5.3.3 Structural analysis

Models were initially fitted to the experimental semivariograms by eye. All four semivariograms showed a spherical shape with a marked discontinuity at the origin ("nugget effect"). The nugget effect is usually ascribed to microregional effects that are too small to be explicitly defined by the data points. In the spherical model, the variance of the field increases with distance until, at a distance called the range, it levels off at a value approximately equal to the global variance of the data points (the sill).

The semivariograms for 1 and 2-day RBAR show similar characteristics, with a small nugget effect and some variability around the sill. Again, the semivariograms for 1 and 2-day CV also resemble one another in shape, this time having a more marked nugget and less irregularity after reaching the range.

Model parameters were fitted using the cross-validation procedure proposed by Delhomme (1978). In this method, each data point is taken out in turn and point kriging is performed with the remaining sample points in order to estimate the value at that point. A number of criteria based on the mean difference between observed and estimated point values are then used to determine the optimum parameters. Details are given in Appendix 2. The fitted parameters are shown in Table 3.

Table 3 Semivariogram model parameters for ln [Z(x) + A]

Basic variable (Z(x))	Nuggett (c0)	Sill (c1)	Range (a) km
1-day RBAR	0.045	0.190	35.0
2-day RBAR	0.007	0.090	35.0
1-day CV	0.026	0.016	40.0
2-day CV	0.023	0.020	35.0

5.3.4 Kriging

Kriging is a linear unbiased interpolation technique used to estimate values of a regionalized variable at unmeasured points. The semivariogram model is the basis of the kriging system. Values are assigned to points on a regular grid according to a linear combination of the point observations, and a measure of the estimation variance, or kriging variance, is given. The procedure has the advantage that the original values at observed points are honoured.

Kriging was carried out on the 1 and 2-day RBAR and CV values using the semivariogram models already described. The method adopted was that of strict kriging, using the Krigpak software package within UNIRAS. The method of sliding neighbourhoods was used (Journel & Huijbregts, 1978), in which kriging is performed using only those sample values that lie within the neighbourhood of the point to be estimated. This helps to correct for non-stationarity in the underlying distribution. Since the semivariogram models seemed to be well defined up to a distance of 120 km, this was used as the radius of influence in the kriging process. Points were kriged onto a regular grid of interval 1 km. An inverse log transformation was carried out to produce grid values in millimetres, which were then contoured to produce the maps in Fig. 4 a-d.

5.3.5 Results

The 1 and 2-day RBAR maps (Fig. 4 a & b) show similar patterns, with high values occurring in the upland regions of Exmoor and Dartmoor. The relatively high values of CV of extreme 1 and 2-day rainfalls in the area around Bridgwater in Somerset are clearly demonstrated in Fig. 4 c & d. This is in agreement with the findings of Bootman & Willis (1977 & 1981) and Reed & Dales (1988).

6. Focussed rainfall growth estimation

6.1 INTRODUCTION

The second stage of the analysis of rainfall frequency in South West England has been concerned with the construction of 1 and 2-day rainfall growth curves. In selecting a new procedure for rainfall frequency estimation, the following properties were identified as desirable. The method should:

(1) fully exploit the daily rainfall data,

(2) avoid fixed geographical regions or at least minimize boundary problems,

(3) provide, through regionalization, estimates of relatively high return period rainfalls, including the 10,000-year event,

and

(4) avoid undue regionalization in the estimation of design rainfalls of moderate return period.

The approach taken to the problem has been to modify the so-called "station-year" method to incorporate the concept of spatial dependence in point rainfall extremes.

6.2 THE STATION-YEAR METHOD

The requirement for estimates of high return period events was met in the Flood Studies Report by partial recourse to the station-year method. In the derivation of regional flood growth curves the assumption was made that the largest four standardized flood peaks from groups of N stations of average record length m years could be assigned plotting positions in the extreme value analysis consistent with them being the largest four events in m.N years of record (FSR I.2.6.2); however, care was taken to avoid near neighbours in the *a priori* grouping of stations. Using the Gringorten formula, the plotting position of the ith highest standardized value is:

$$y_i = \ln(-\ln F_i) \qquad (2)$$

where y is the Gumbel reduced variate, F is the non-exceedance probability:

$$F_i = (i - 0.44) \;/\; (M + 0.12) \qquad (3)$$

and M = m.N is the number of station-years of record.

A similar assumption was made in the derivation of rainfall growth factors (FSR II.2.3) but without the safeguard of segregating near-neighbour stations.

The station-year method has been widely criticized because it assumes spatial independence in hydrological extremes. There is, however, considerable spatial dependence in rainfall extremes and this undoubtedly contributes to spatial dependence in floods. In effect, the N stations of average record length m years provide many fewer than m.N independent station-years of record. Thus the station-year method has a gross error which is only partly corrected by its similar neglect of dependence in the highest values themselves. (The FSR's treatment of the four highest standardized floods allowed particular events such as the September 1968 floods to supply more than one station-year point.)

6.3 A MODEL OF SPATIAL DEPENDENCE IN MAXIMUM RAINFALLS

Reed & Dales (1988) present a simple model for spatial dependence in maximum rainfalls. For any network of N sites, an effective area spanned (AREA km^2) is identified and a regression model applied to estimate an equivalent number of independent sites, N_e:

$$\ln N_e \;/\; \ln N = a + b \ln AREA + c \ln N + d \ln D \qquad (4)$$

where D is the rainfall duration in days. The UK average model is:

$$\ln N_e = \ln N(0.081 + 0.085 \ln AREA - 0.051 \ln N - 0.027 \ln D) \qquad (5)$$

Thus, for example, four sites spanning 1000 km^2 are deemed equivalent to 2.29 independent sites for 1-day maximum rainfalls.

6.4 A MODIFIED STATION-YEAR METHOD

The spatial dependence model provides a means of correcting the deficiencies of the station-year method. For a fixed network of N gauges operating for m years the equivalent number of independent station-years, M_e, is simply $m.N_e$. However, in practice, the number of gauges operating varies from year to year and M_e is instead calculated by accumulating values of N_e year by year. In the modified station-year method, the r largest independent standardized values are plotted as the r largest events in a record length of M_e station-years, again using the Gringorten formula (Equation 3) but with M_e replacing M. Thus the method gives emphasis to the most extreme events observed in a region.

The modified station-year approach forms the basis of the focussed rainfall growth estimation (FORGE) method. This is designed to produce a rainfall growth curve that is centred on a particular location. The FORGE method meets the criterion to provide regionalized estimates of high return period events while keeping faith with what more local data infer about events of moderate return period.

6.5 FOCUSSED RAINFALL GROWTH CURVES FOR SOUTH WEST ENGLAND

6.5.1 The FORGE method

The FORGE method has been used to construct a series of 1 and 2-day rainfall growth curves focussed on ten locations in South West England. These locations, which are shown in Fig. 5, were chosen to give approximately even coverage of the study region, and it can be seen that the area studied by Bootman & Willis (1977 & 1981) is well represented.

The analysis was carried out using daily rainfall data from 1255 raingauges. Of these, 590 were situated within the region of study (see Table 1). The remainder were included either because they were adjacent to the study region, or because they had reliable records of greater than 40 years. Annual maximum 1 and 2-day rainfall series were constructed for each gauge and standardized by the relevant RBAR value at that gauge, each series comprising at least ten values. The standardized annual maxima provided the input dataset for the FORGE analysis.

The FORGE method is largely a graphical one in which an extreme value plot of standardized data is constructed by a series of applications of the modified station-year method.

In the first application, the three gauges nearest to the focal point are analysed. For each year containing at least one annual maximum value, the equivalent number of independent sites is calculated using the spatial dependence model. The N_e values are then cumulated over all the years of record to give the equivalent number of independent station-years, M_e. The six highest independent standardized values are plotted using plotting positions based on Equations 2 and 3, before the analysis is repeated for a larger network of gauges.

In the second application, data are analysed for the six stations nearest to the focal point. Again the six highest independent standardized values are abstracted. Because the larger network provides more equivalent independent station-years, the points plot further to the right in the extreme value plot.

The analysis continues, doubling the number of gauges each time. As gauges at a greater distance from the focal point are gradually included, the reliability of their records becomes more important since they are being used to estimate rainfall frequency at higher return periods. For this reason, in order to be included in the analysis, gauges at a distance of more than 50 km from the focal point must have more than 20 annual maxima. Similarly, gauges more than 100 km from the focal point must have more than 30 maxima, and gauges more than 150 km away must have more than 40 values. Thus, the final iteration incorporates all gauges in the UK with more than 40 years of data, as well as those local gauges with reliable records.

Reed & Dales (1988) provide different sets of parameters for the spatial dependence model for each of the regions shown in Fig. 1. In the application of the FORGE method to South West England, the means of the parameter values for the South West and West Country regions were used. Thus, Equation 4 becomes:

$$\ln N_c = \ln N \, (0.098 \ln AREA - 0.0715 \ln N + 0.0 \ln D) \qquad (6)$$

However, in most practical cases the resultant interregional differences in assessments of spatial dependence are generally slight and it is suggested that wider applications of the modified station-year method might reasonably adopt the UK average model (Equation 5).

6.5.2 Results

The forms of the 1 and 2-day rainfall growth curves for the ten foci in South West England are shown in Figs. 6 and 7. Individual curves were sketched in to follow the points plotted in the FORGE method and are given in Figs. 8 and 9 (a to j).

The characteristic S-shape of the growth curves is illustrated in Figs. 6 and 7. That the different curves approach one another at high return period is a feature of the FORGE method. The reason for this is this that long-term gauge records from the whole of the UK are included in the final iteration of the graphical method. Therefore the very highest standardized rainfalls are likely to be common to each focussed growth curve, with the plotting positions varying slightly due to differences between sites in the final number of independent station-years.

From Fig. 6 it can be seen that the 1-day curve focussed on Bridgwater is notably high in the return period range 20 to 200 years, confirming Bootman & Willis' finding that rainfall growth rates in Somerset are especially severe. The curve focussed on Chard is particularly high between return periods of 100 and 300 years. That for Bristol, however, lies beneath the others between return periods of 200 and 1000 years. The curve focussed on Wimbleball Reservoir lies in the middle of the ten curves. The 2-day focussed growth curves (Fig.7) show a similar pattern relative to one another, although the curve for Great Torrington is particularly low between return periods of 50 and 500 years.

In Fig. 10, the 1-day growth curve focussed on Wimbleball Reservoir is shown together with the growth curves for the West Country and South West regions derived by Dales & Reed (1988). It can be seen that up to a return period of about 800 years the Wimbleball curve is remarkably close to that of the West Country. For higher return periods, however, more moderate growth rates pertain.

6.5.3 Discussion

In the study, particular emphasis has been placed on the requirement to derive estimates of design rainfalls of high return period for Wimbleball Reservoir. In Figs. 11 and 12, 1 and 2-day rainfall frequencies in millimetres derived using the FORGE method are compared with FSR estimates for Wimbleball. The large departures from the curve based on the FSR method are obvious at all return periods for 1-day rainfalls and at return periods of greater than 50 years for 2-day rainfalls.

Estimates of 10,000-year return period rainfalls for Wimbleball are given in Table 4.

Table 4 Comparison of 10,000-year rainfall estimates for Wimbleball Reservoir

	10,000-year rainfall (mm)	
	FORGE	FSR II
1-day duration	264	239
2-day duration	314	266

Similarly, rainfall frequency curves centred on Bridgwater are shown in Figs. 13 and 14. In this case, estimates of design rainfalls derived by the FORGE method exceed those of the FSR method at all return periods.

6.5.4. Link with FSR II

Use of the FORGE analysis technique in South West England has indicated particular shortcomings in the FSR II method when applied to the region. Methods of linking the results of the analysis to the standard FSR method, for example by computing correction factors, are currently being investigated.

7. Conclusion

In this study a two-stage approach to the analysis of rainfall frequency in South West England has been undertaken. The results of the analysis indicate significant departures from the FSR II method, and thus have important implications for flood design in the region. The methods used in the analysis are of considerable interest since they could be applied to any region of the UK, provided sufficient data were available.

The use of the kriging technique in mapping RBAR values has demonstrated the value of the geostatistical approach in the analysis of rainfall statistics. In view of the relationship between RBAR and altitude, it is thought that extension of the technique to incorporate regression could produce maps of higher quality if digital elevation data were available.

The FORGE method provides a new and powerful technique for estimating rainfall growth curves where sufficient data are available. Development of the technique is continuing and the possibility of seeking parametric forms for the growth curves is being investigated.

8. References

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Figure 1a *UK rainfall regions presented by Reed & Dales (1988).*

Figure 1b *Interregional comparison of typical growth curves fitted to standardized 1-day annual maximum rainfalls (from Reed & Dales, 1988).*

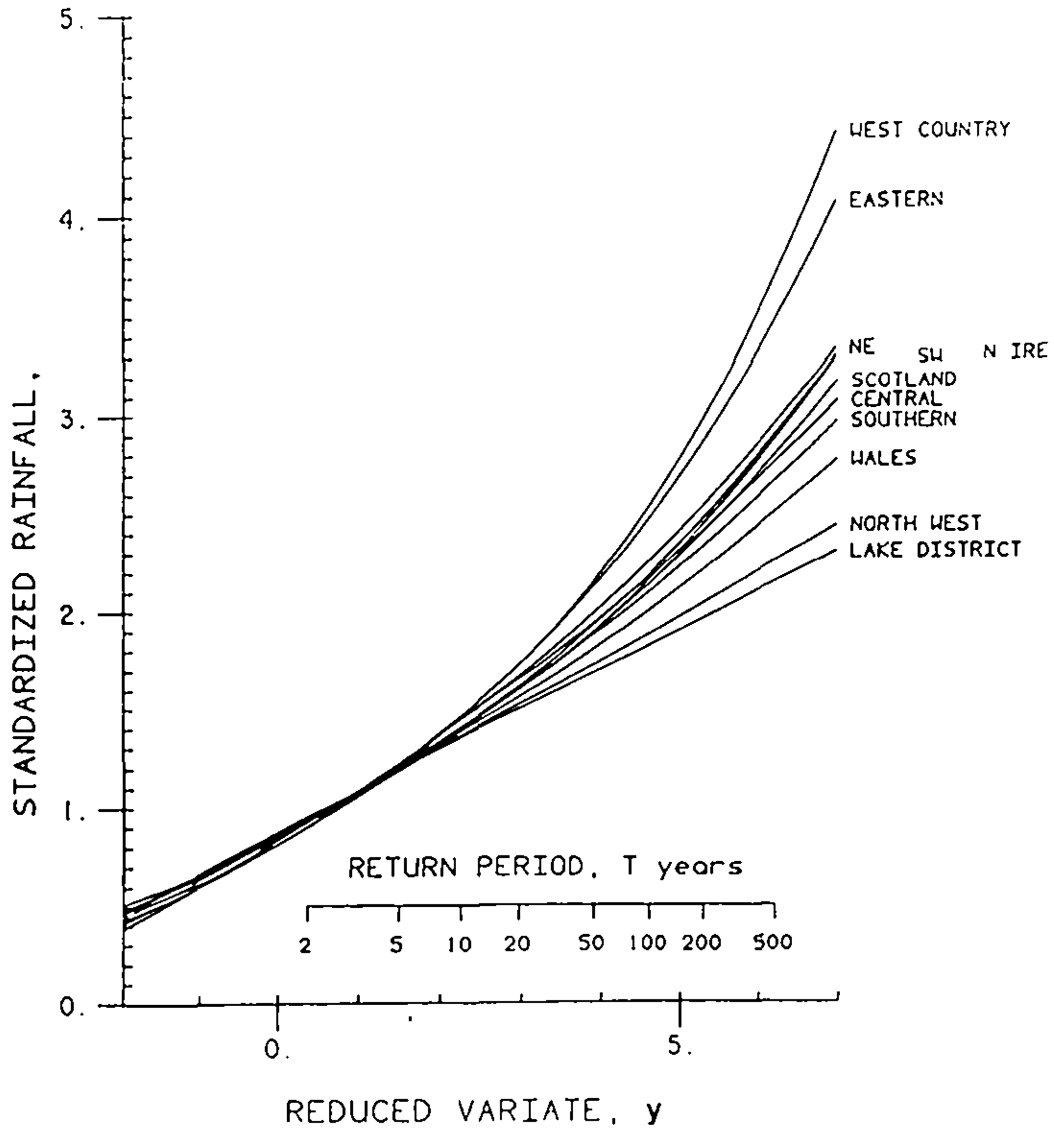


Figure 2 Location of raingauges in South West England.

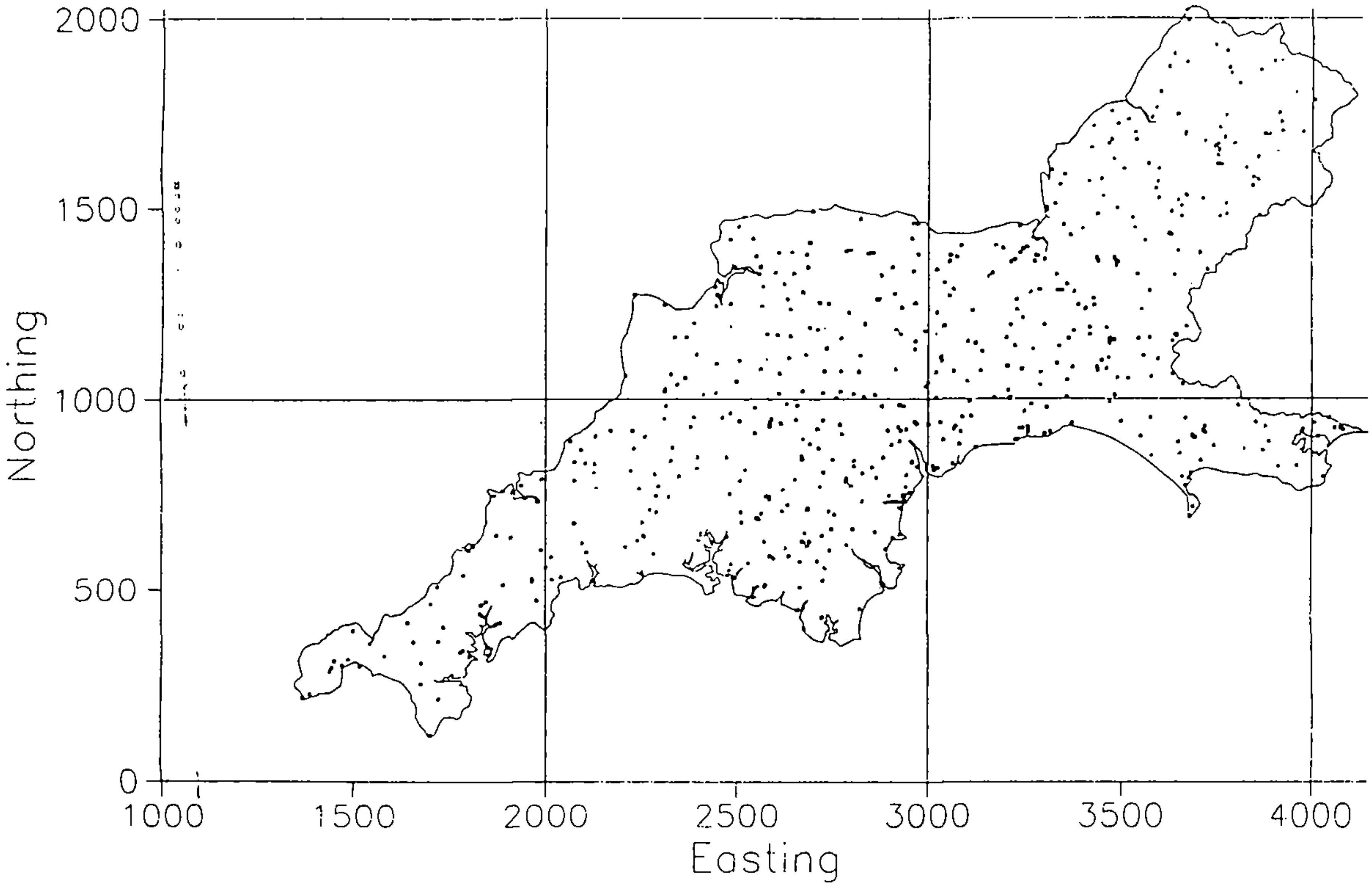


Figure 3a Experimental semivariogram for 1-day RBAR

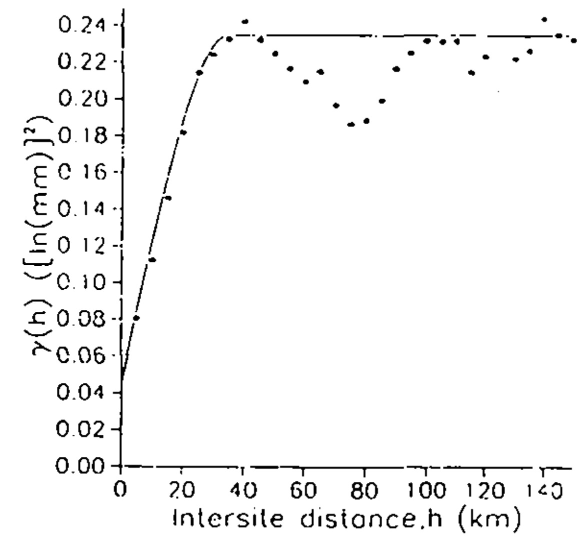


Figure 3b Experimental semivariogram for 2-day RBAR

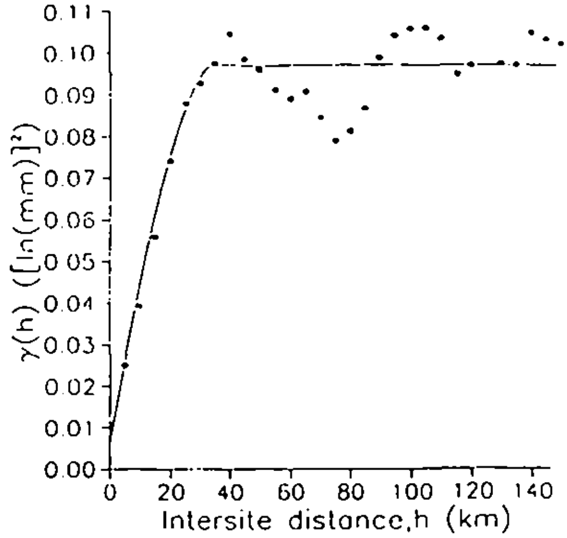


Figure 3c Experimental semivariogram for 1-day CV.

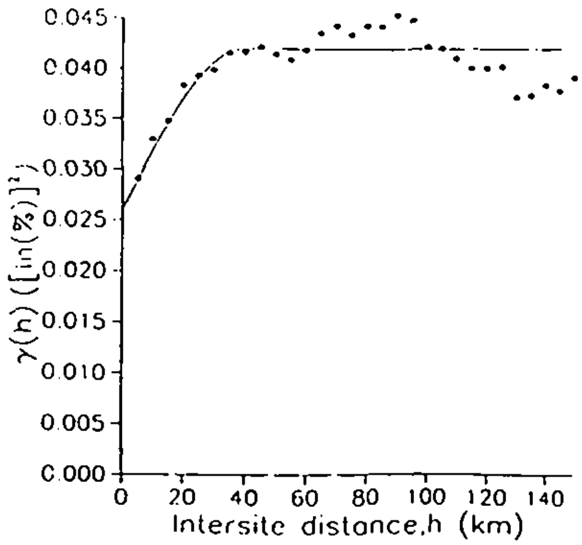


Figure 3d Experimental semivariogram for 2-day CV.

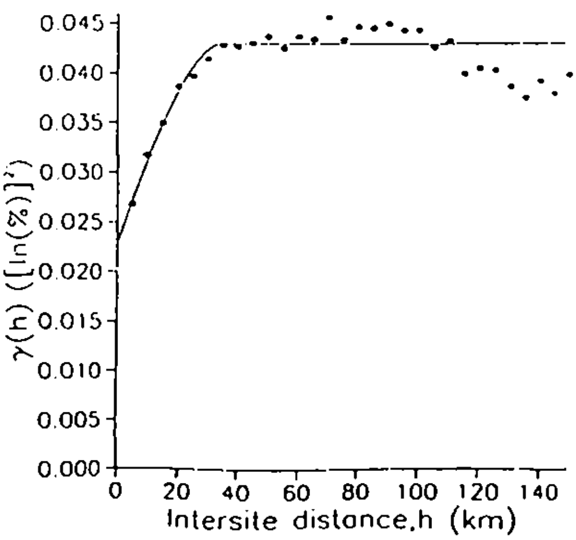


Figure 4a Mean (RBAR) of annual maximum 1-day rainfalls (mm).

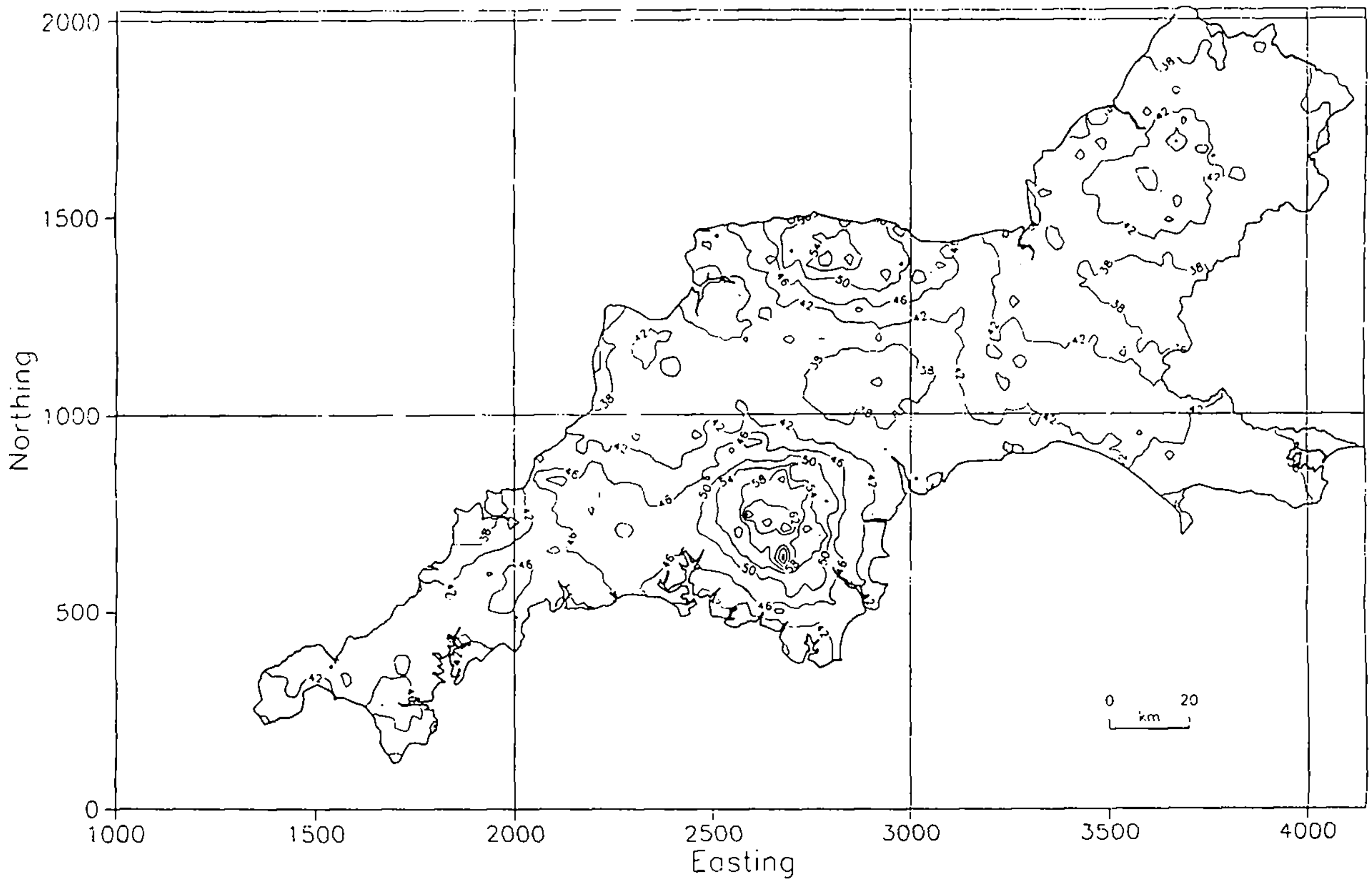


Figure 4b *Mean (RBAR) of annual maximum 2-day rainfalls (mm).*

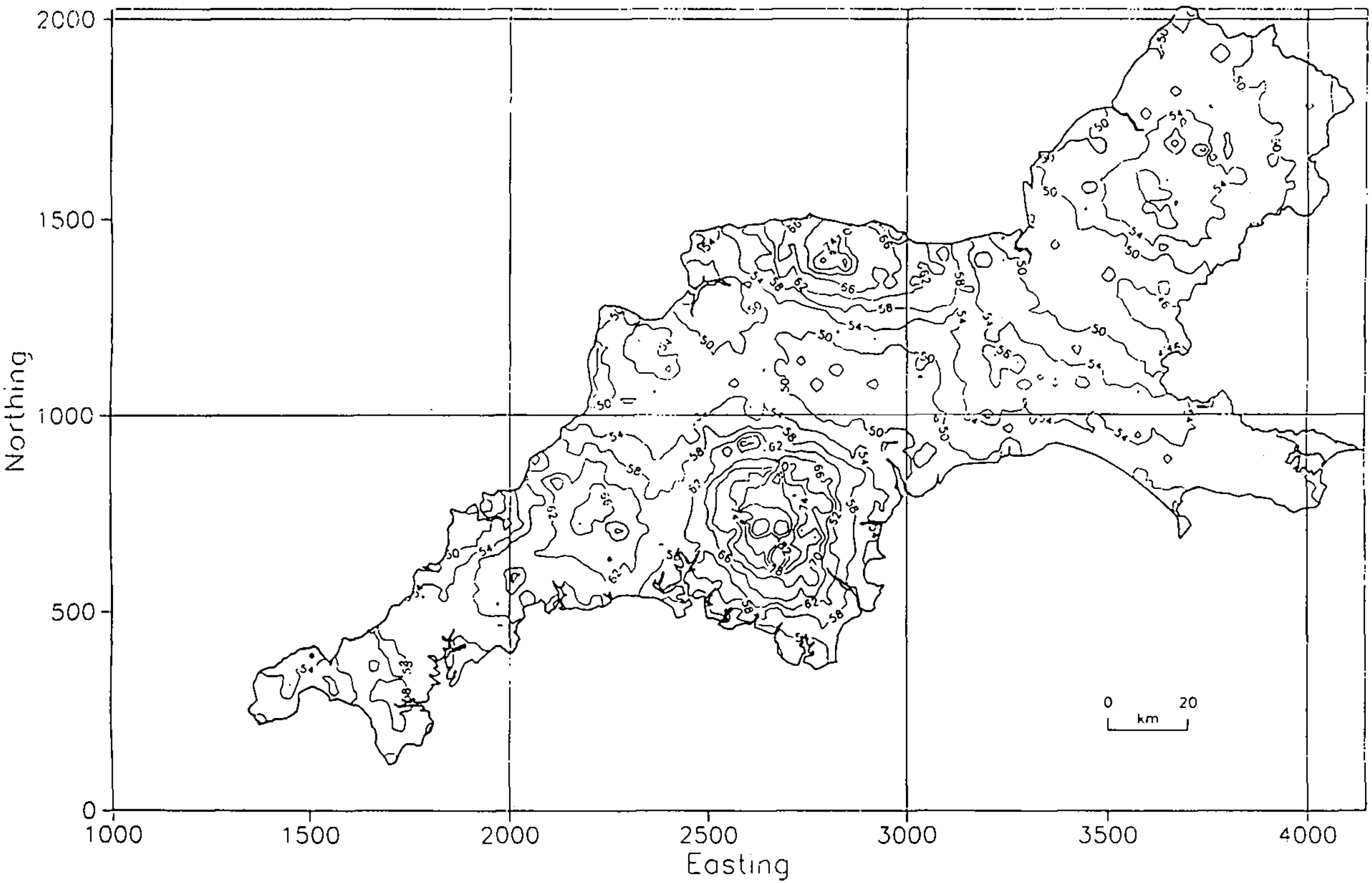


Figure 4c Coefficient of variation (CV) of annual maximum 1-day rainfalls (%).

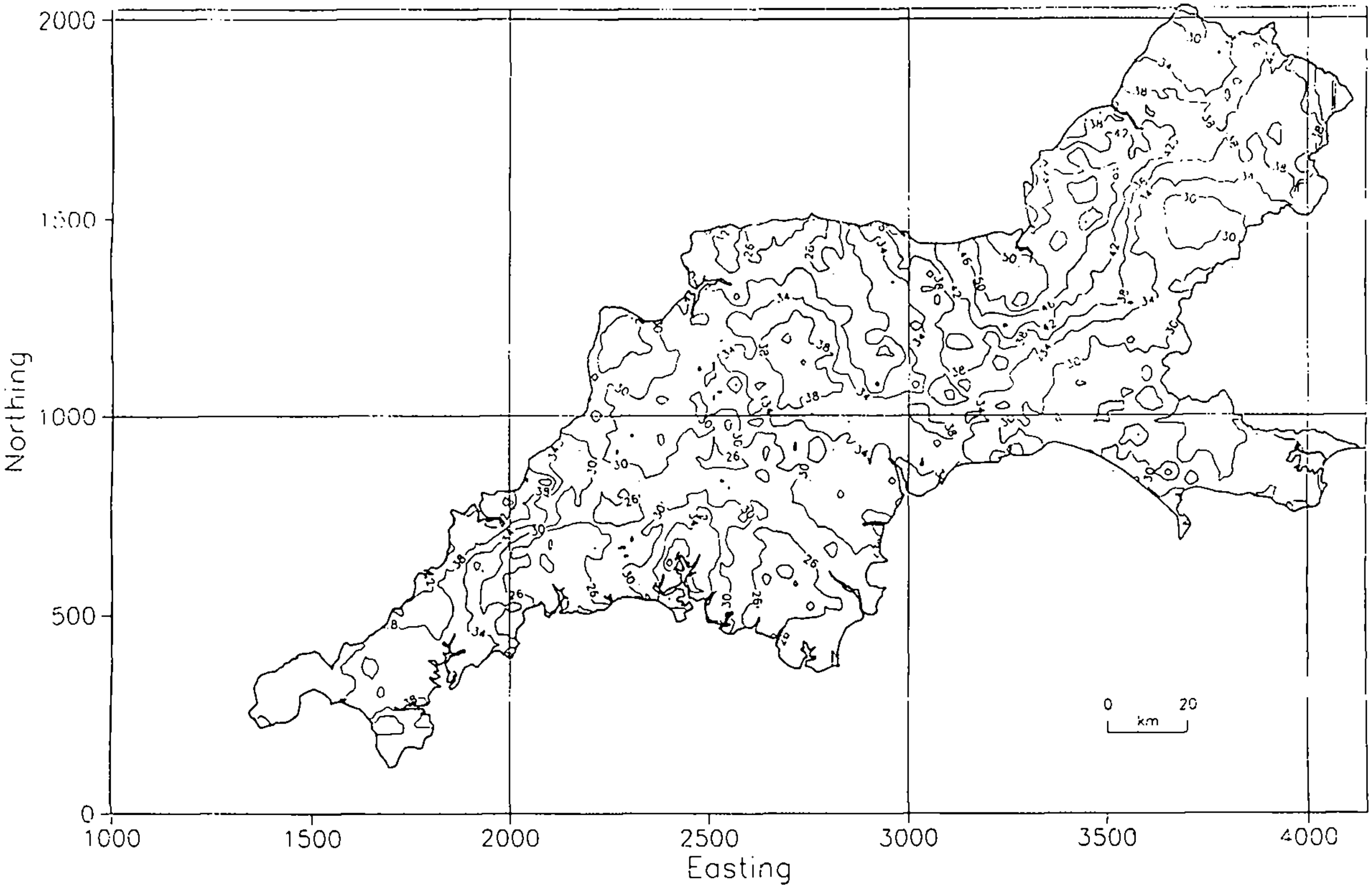


Figure 4d *Coefficient of variation (CV) of annual maximum 2-day rainfalls (%).*

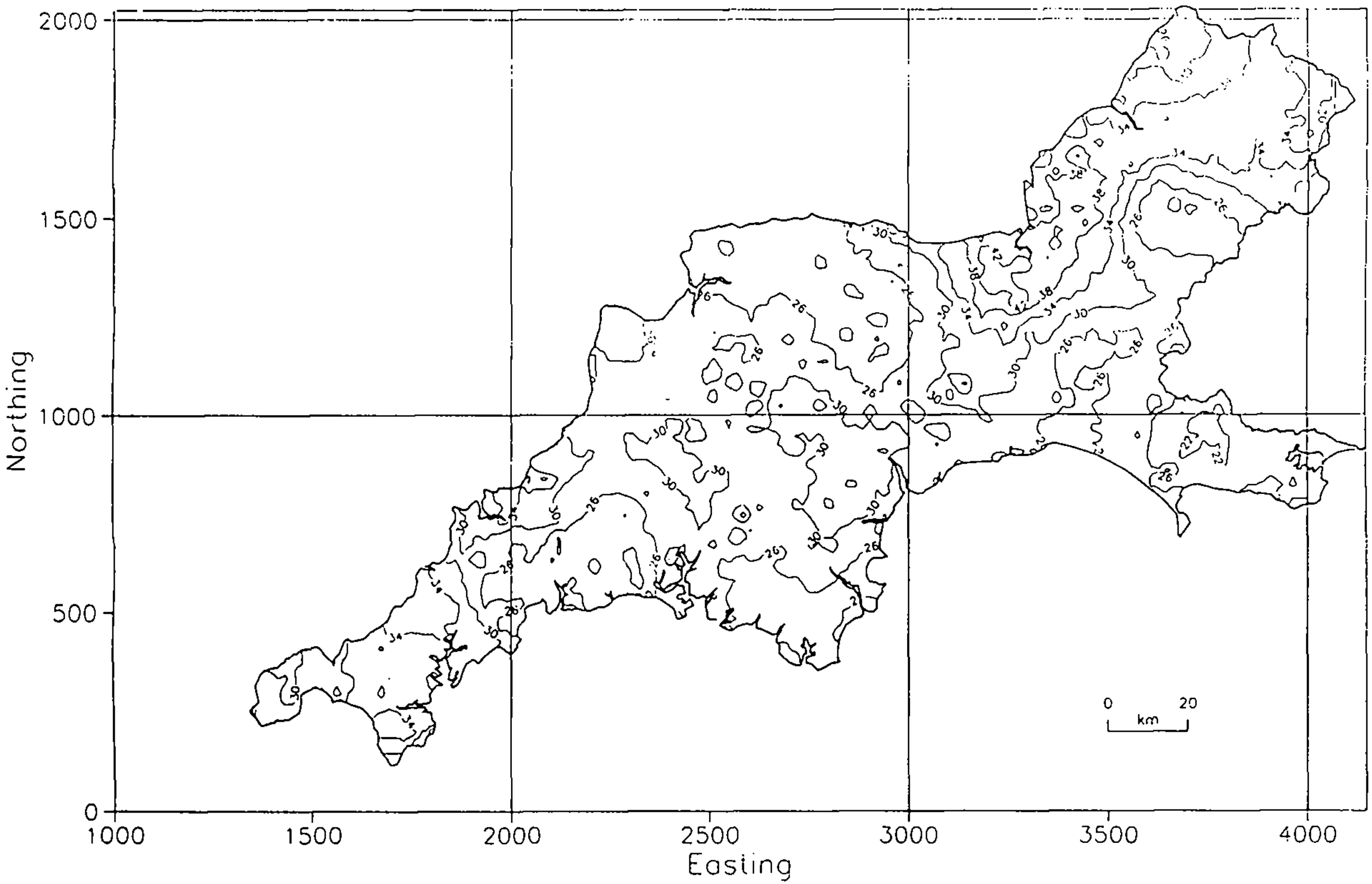


Figure 5 Foci of rainfall growth curves in South West England.

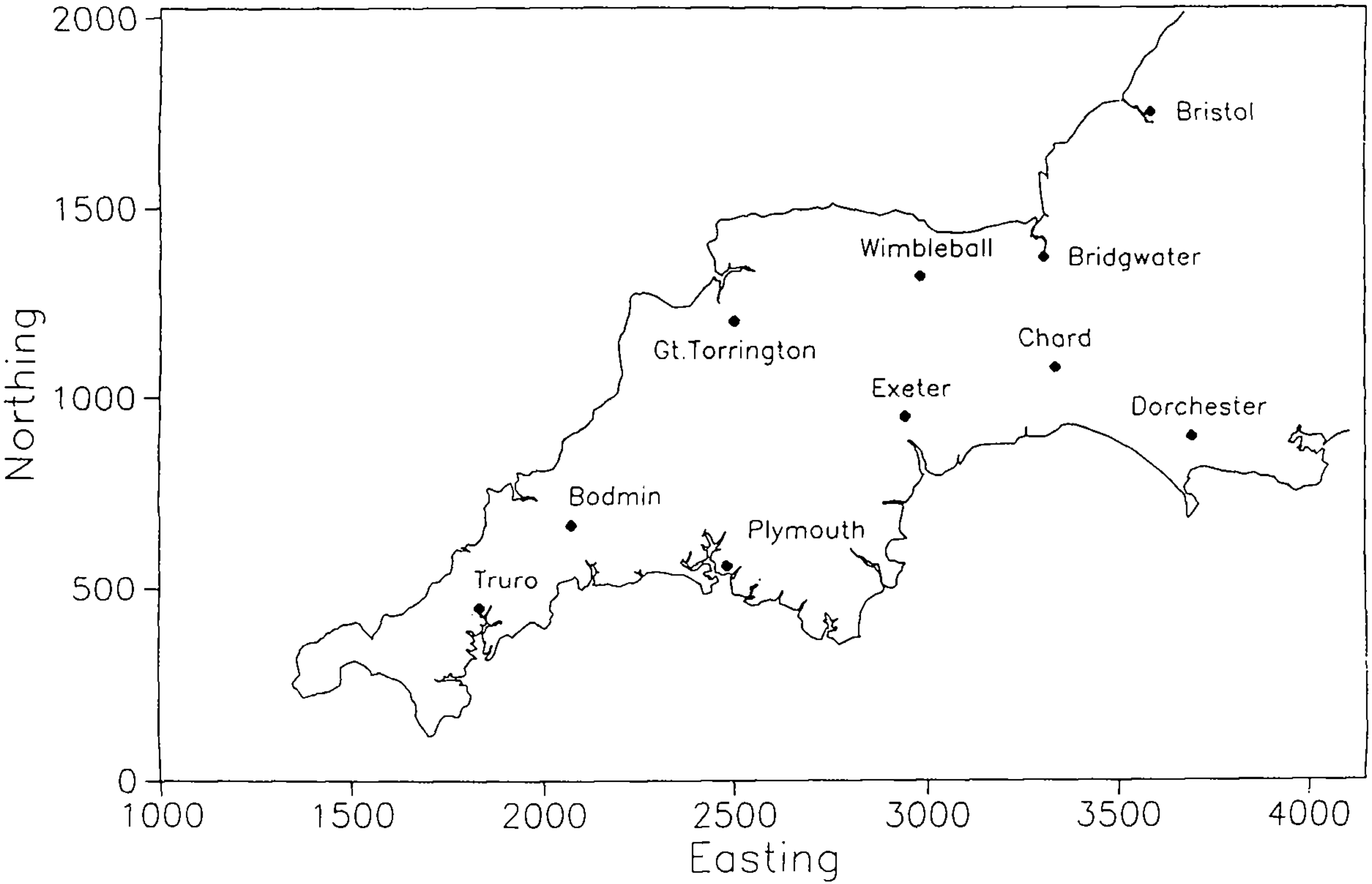


Figure 6 1-day focussed growth curves for South West England.

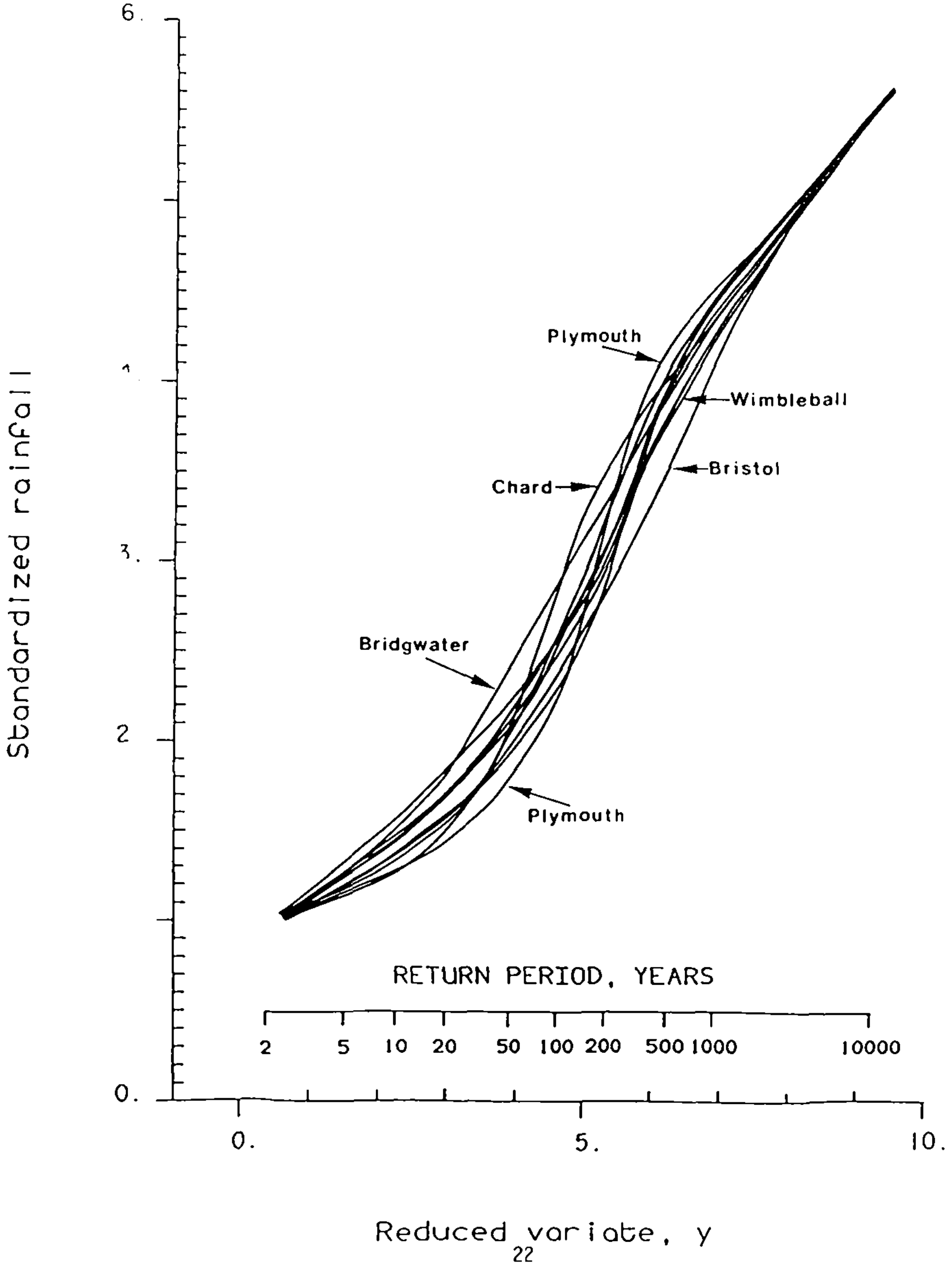


Figure 7 2-day focussed growth curves for South West England

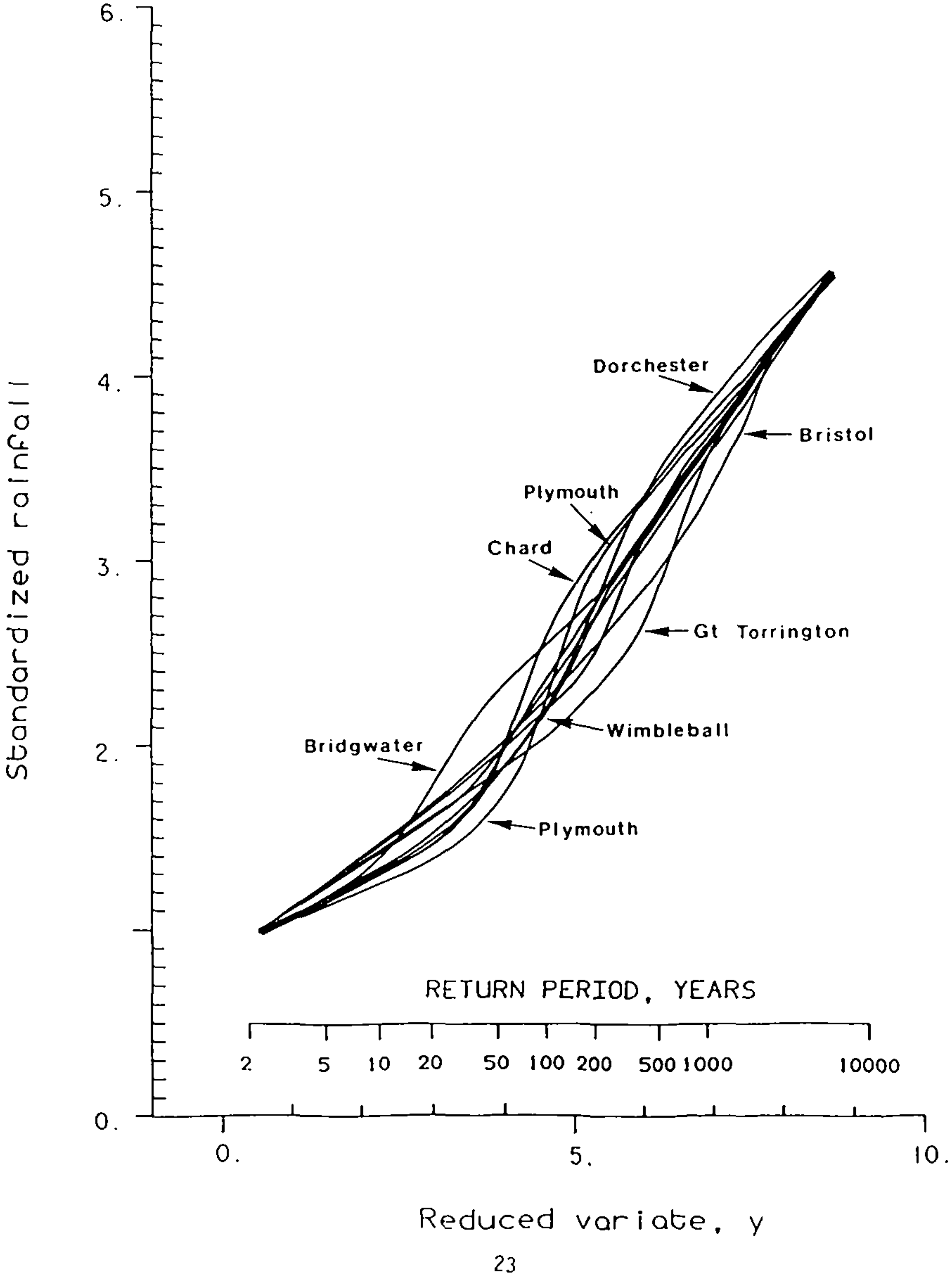
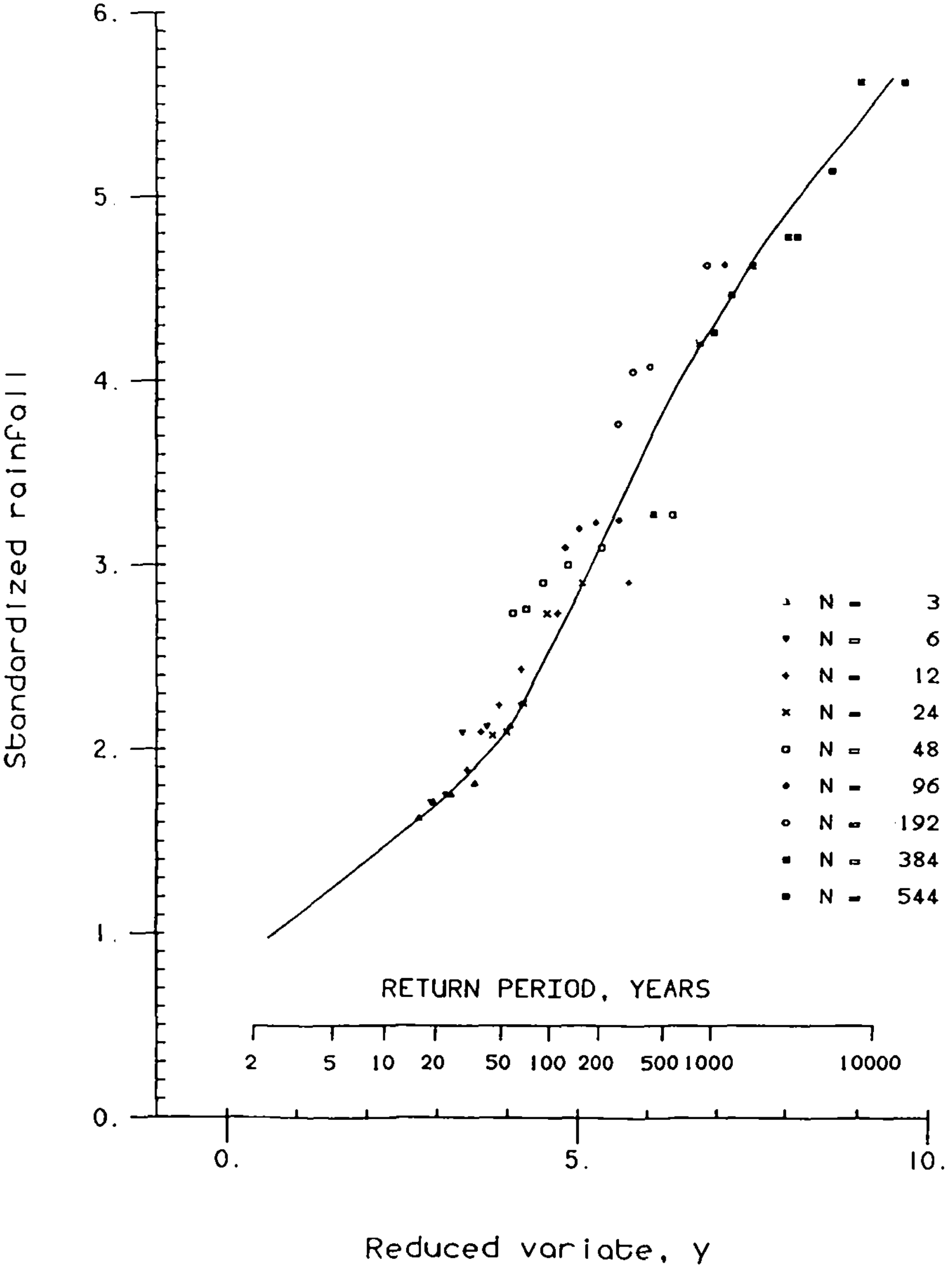


Figure 8 *1-day focussed growth curves for South West England:*

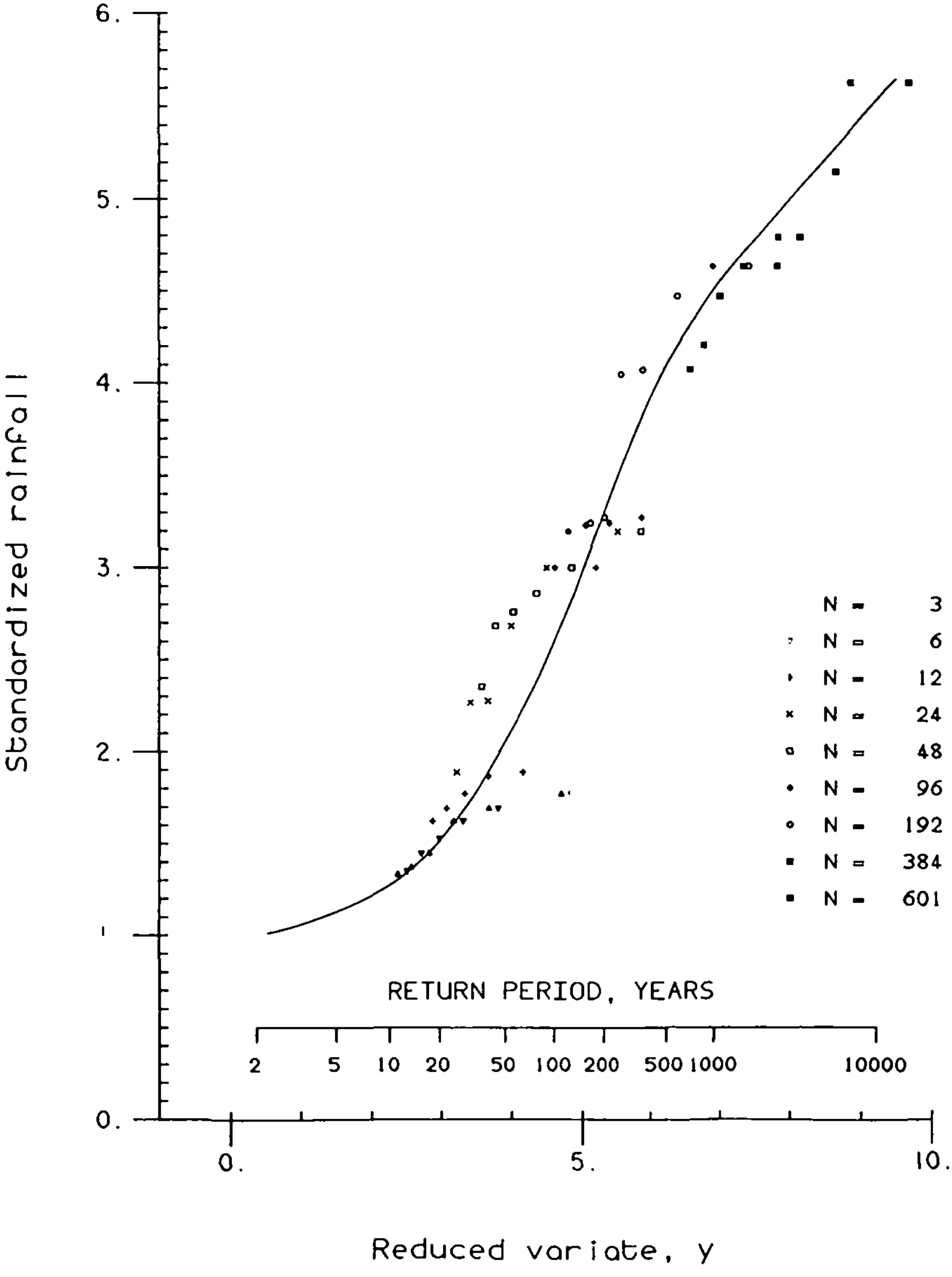
a) Truro
b) Bodmin
c) Plymouth
d) Great Torrington
e) Exeter
f) Wimbleball
g) Bridgwater
h) Chard
i) Bristol
j) Dorchester

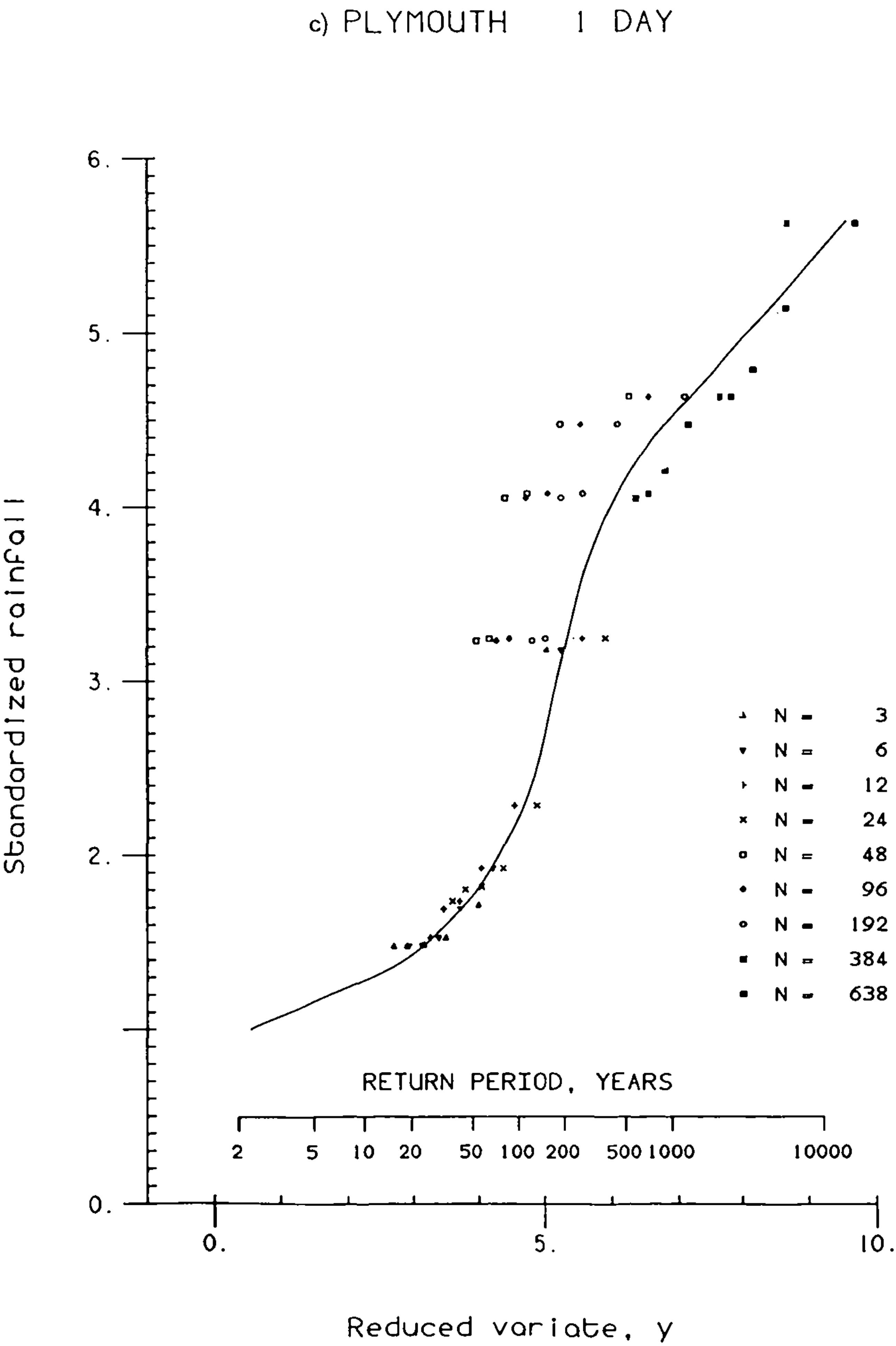
a) TRURO 1 DAY



Standardized rainfall
0.
1.
2.
3.
4.
5.
6.
N = 3
N = 6
N = 12
N = 24
N = 48
N = 96
N = 192
N = 384
N = 544
RETURN PERIOD, YEARS
2
5
10
20
50
100
200
500
1000
10000
0.
5.
10.
Reduced variate, y

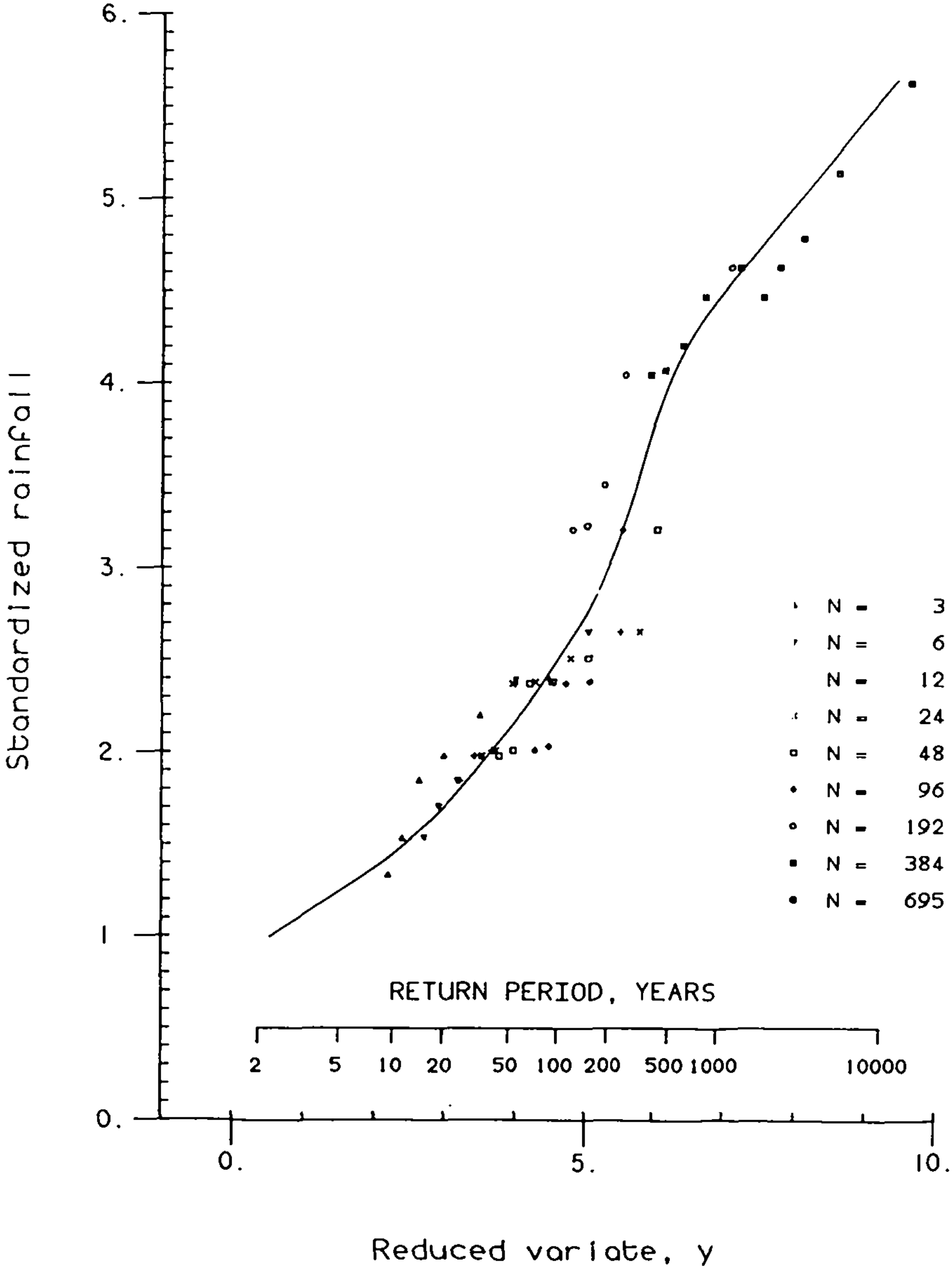
b) BODMIN 1 DAY

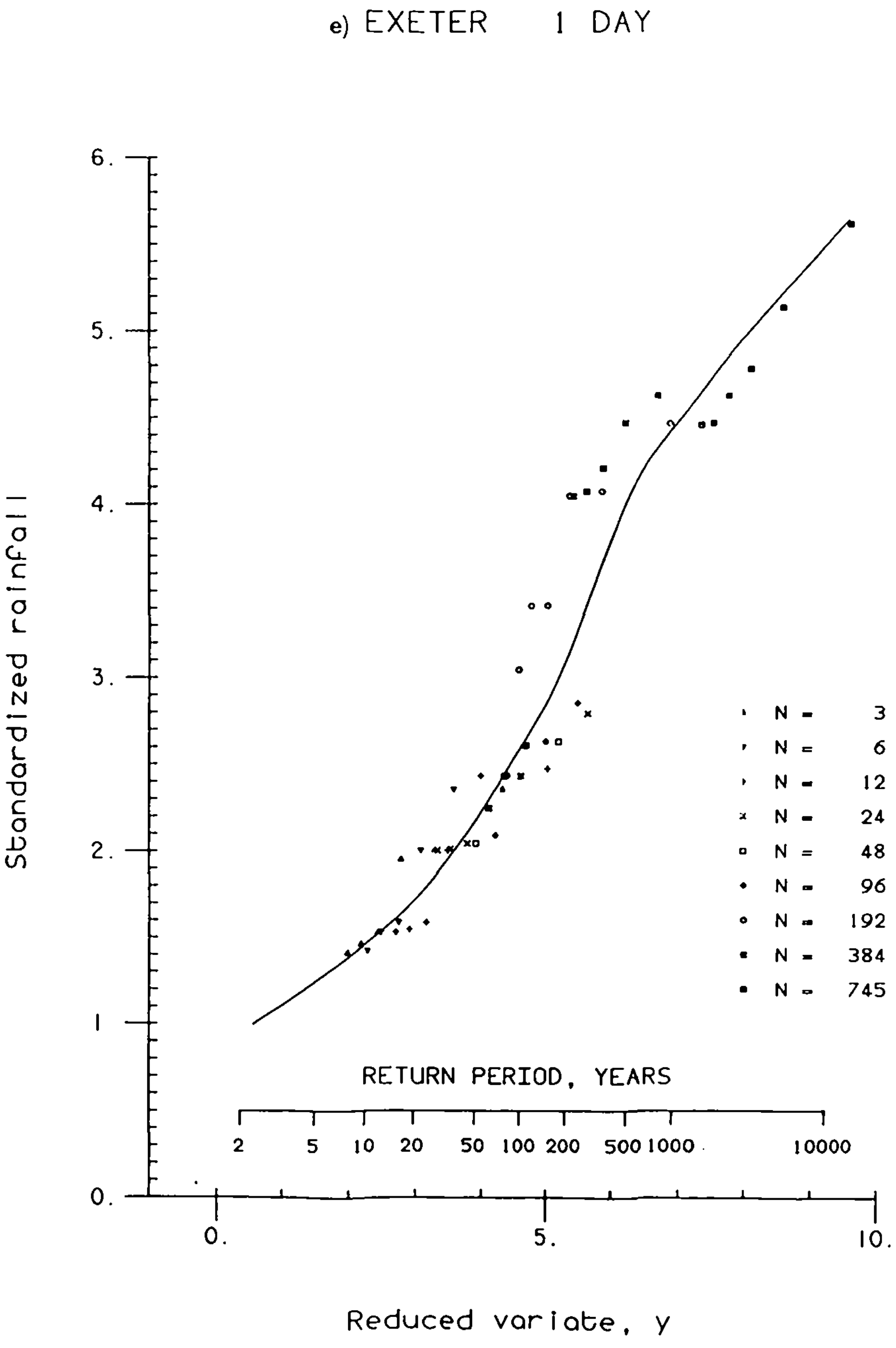




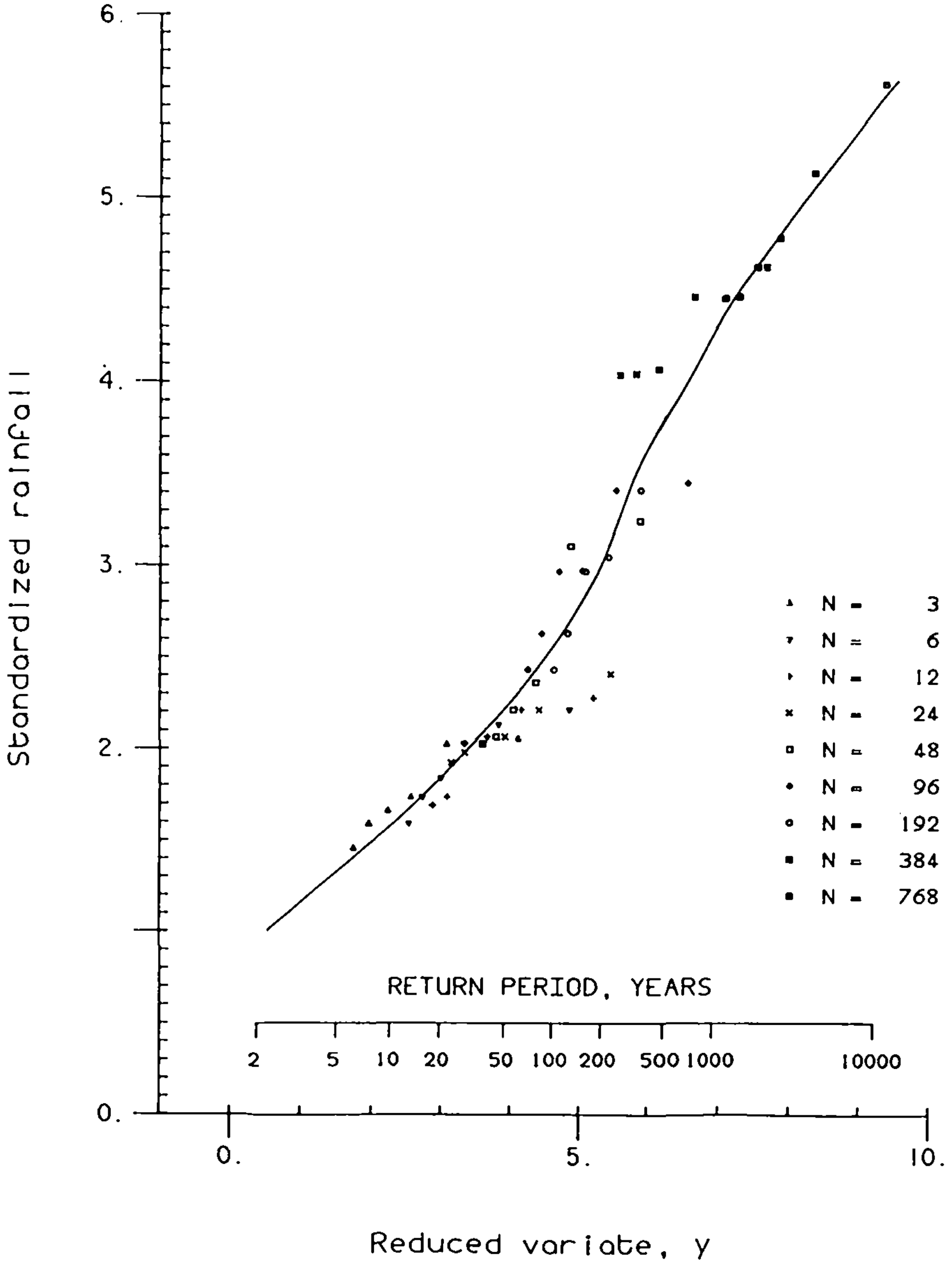
c) PLYMOUTH 1 DAY
Standardized rainfall
6.
5.
4.
3.
2.
0.
RETURN PERIOD, YEARS
2
5
10
20
50
100
200
500
1000
10000
N = 3
N = 6
N = 12
N = 24
N = 48
N = 96
N = 192
N = 384
N = 638
0.
5.
10.
Reduced variate, y

d) GT TORRINGTON - 1 DAY

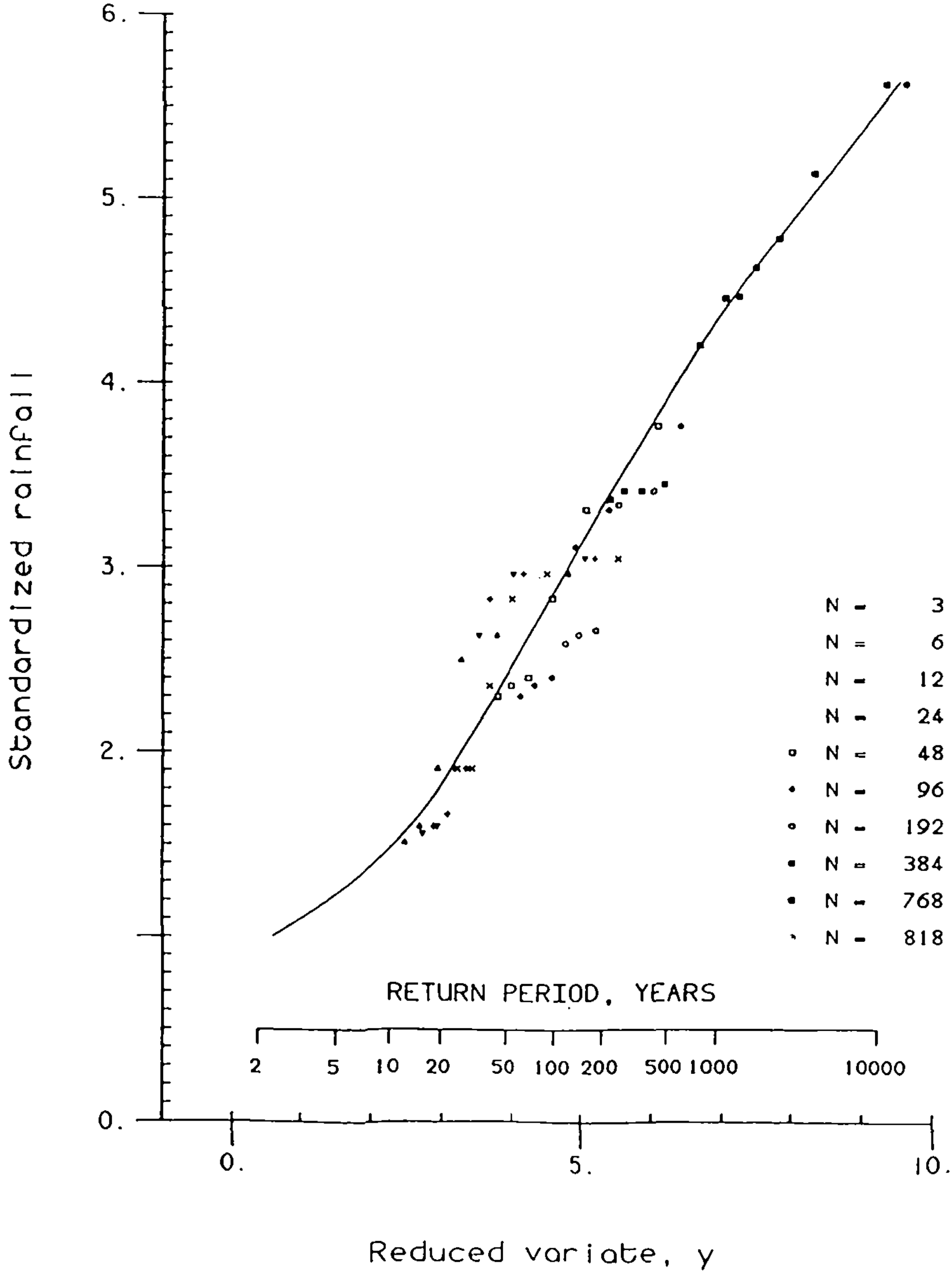



e) EXETER 1 DAY
Standardized rainfall
6.
5.
4.
3.
2.
1
0.
N = 3
N = 6
N = 12
N = 24
N = 48
N = 96
N = 192
N = 384
N = 745
RETURN PERIOD, YEARS
2
5
10
20
50
100
200
500
1000
10000
0.
5.
10.
Reduced variate, y

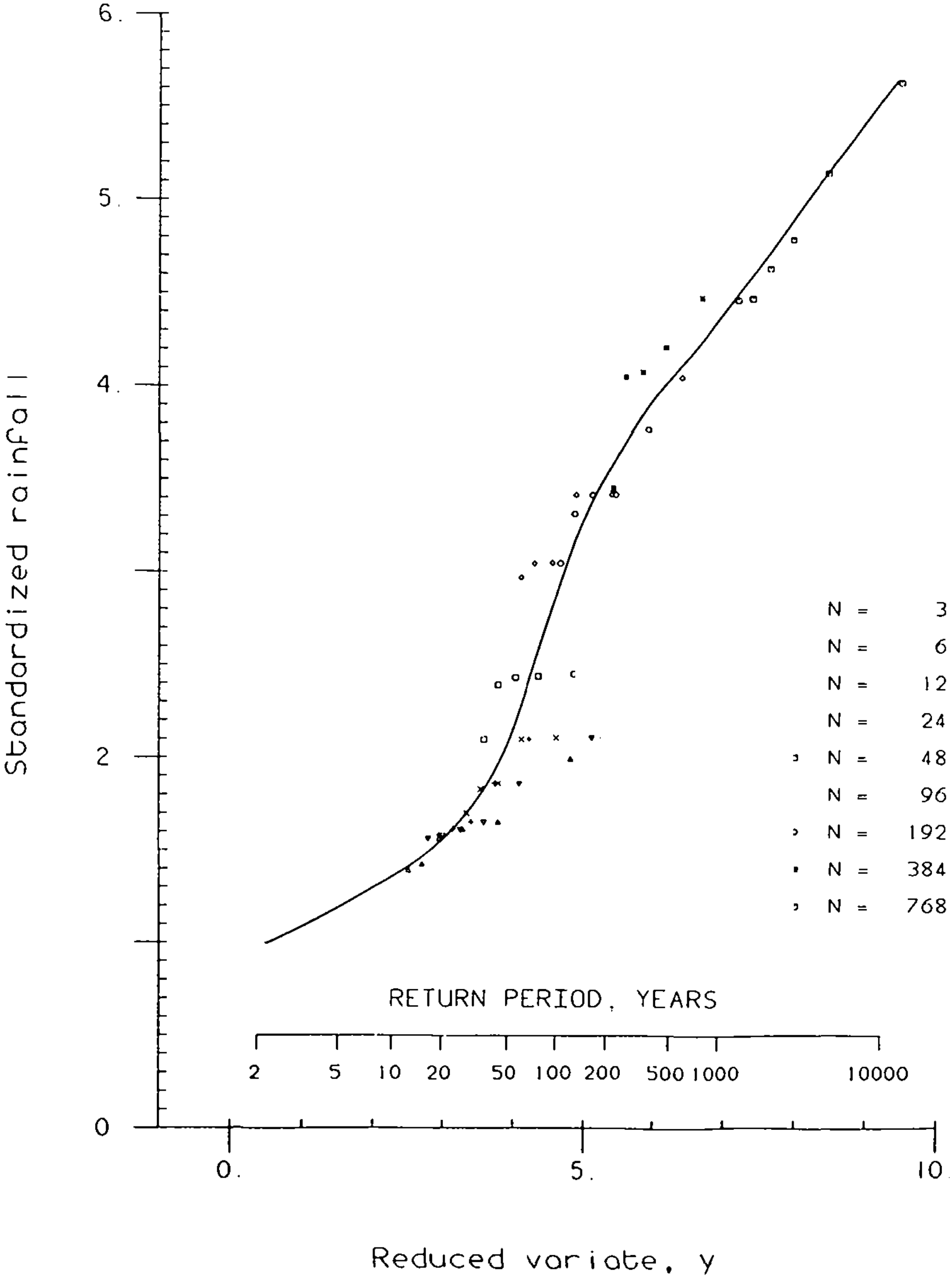
f) WIMBLEBALL 1 DAY



g) BRIDGWATER 1 DAY

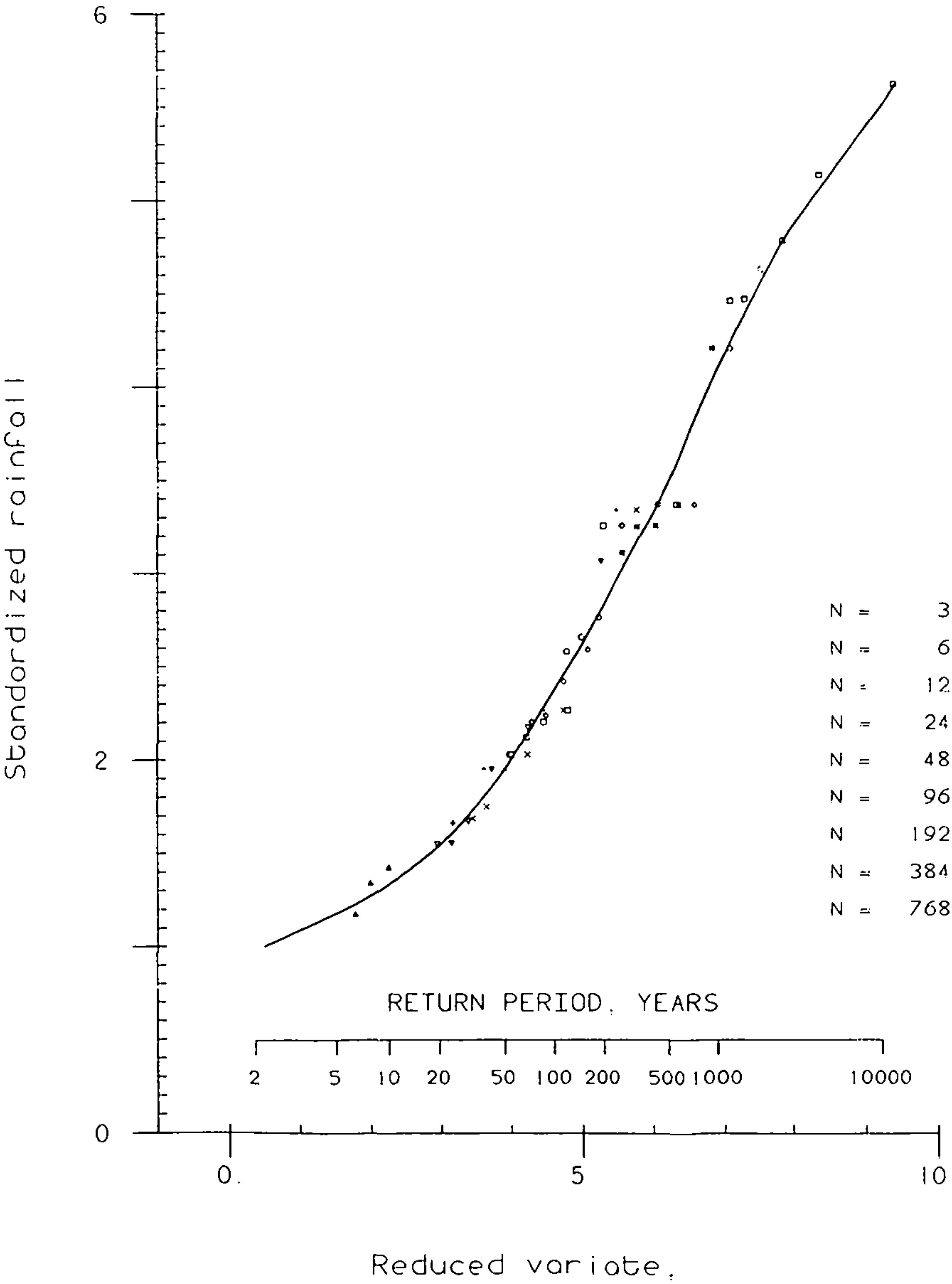


h) CHARD 1 DAY



Standardized rainfall
6.
5.
4.
2
0
N = 3
N = 6
N = 12
N = 24
N = 48
N = 96
N = 192
N = 384
N = 768
RETURN PERIOD, YEARS
2
5
10
20
50
100
200
500
1000
10000
0.
5.
10.
Reduced variate, y

i) BRISTOL DAY



i) DORCHESTER 1 DAY

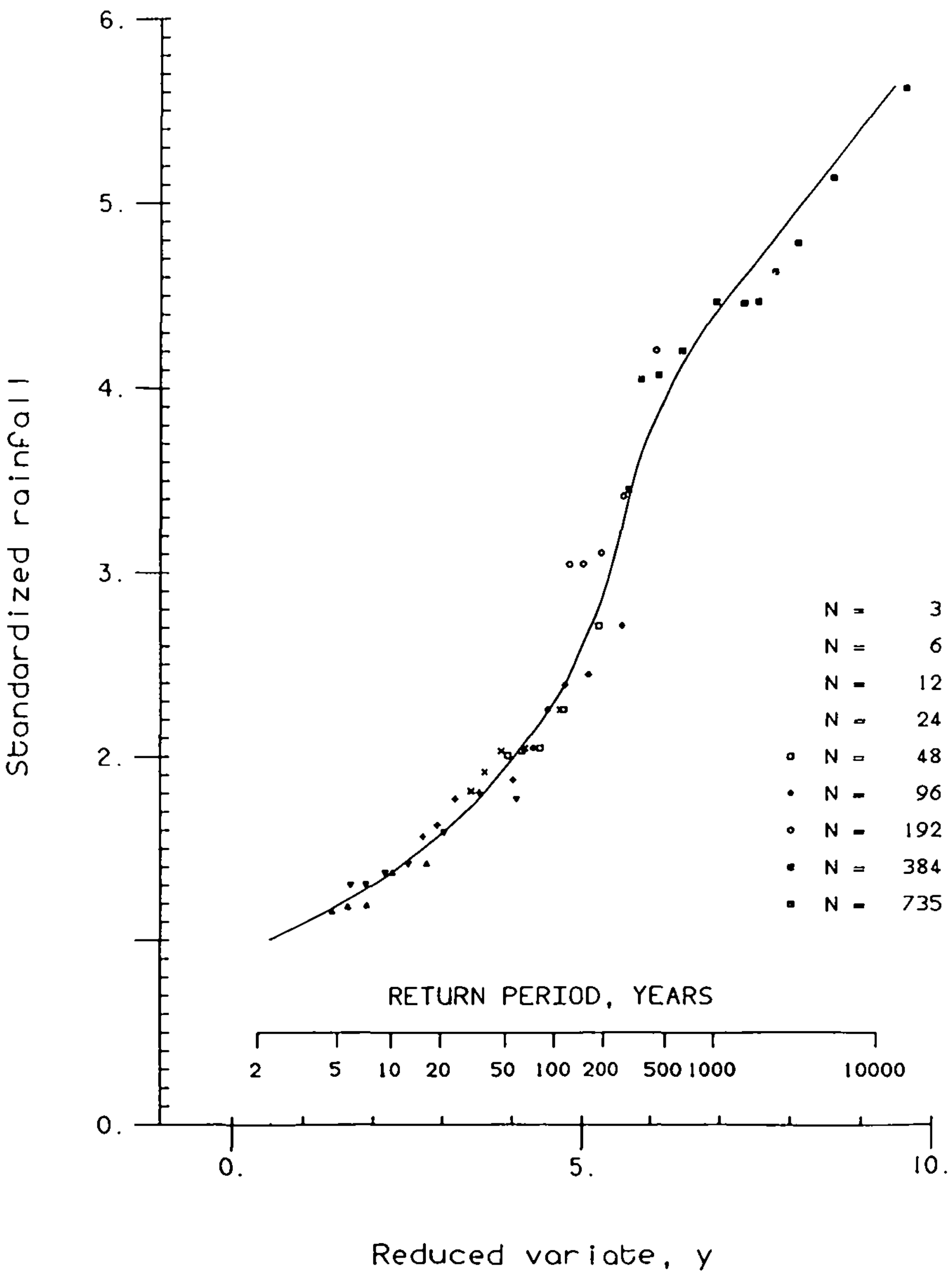
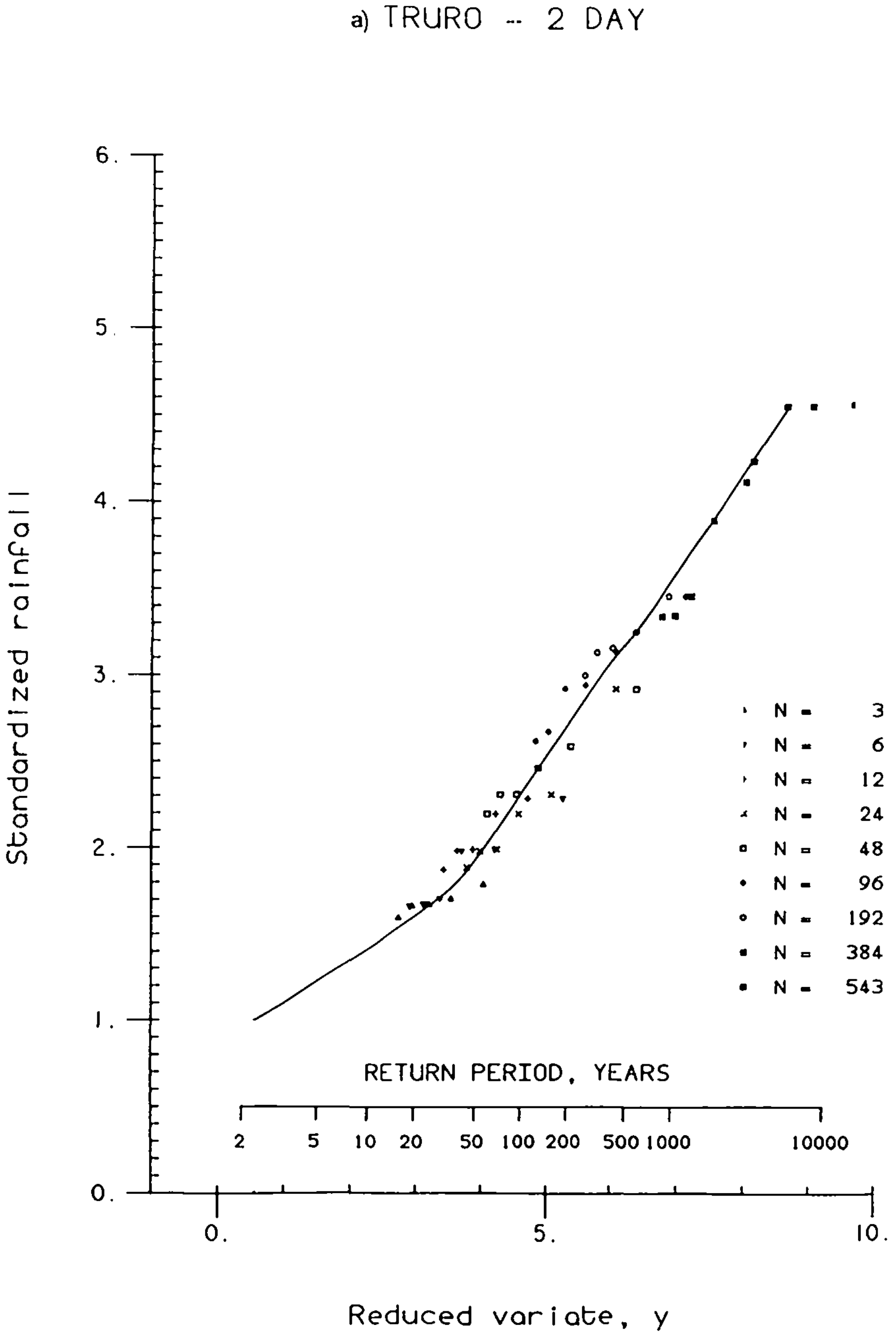
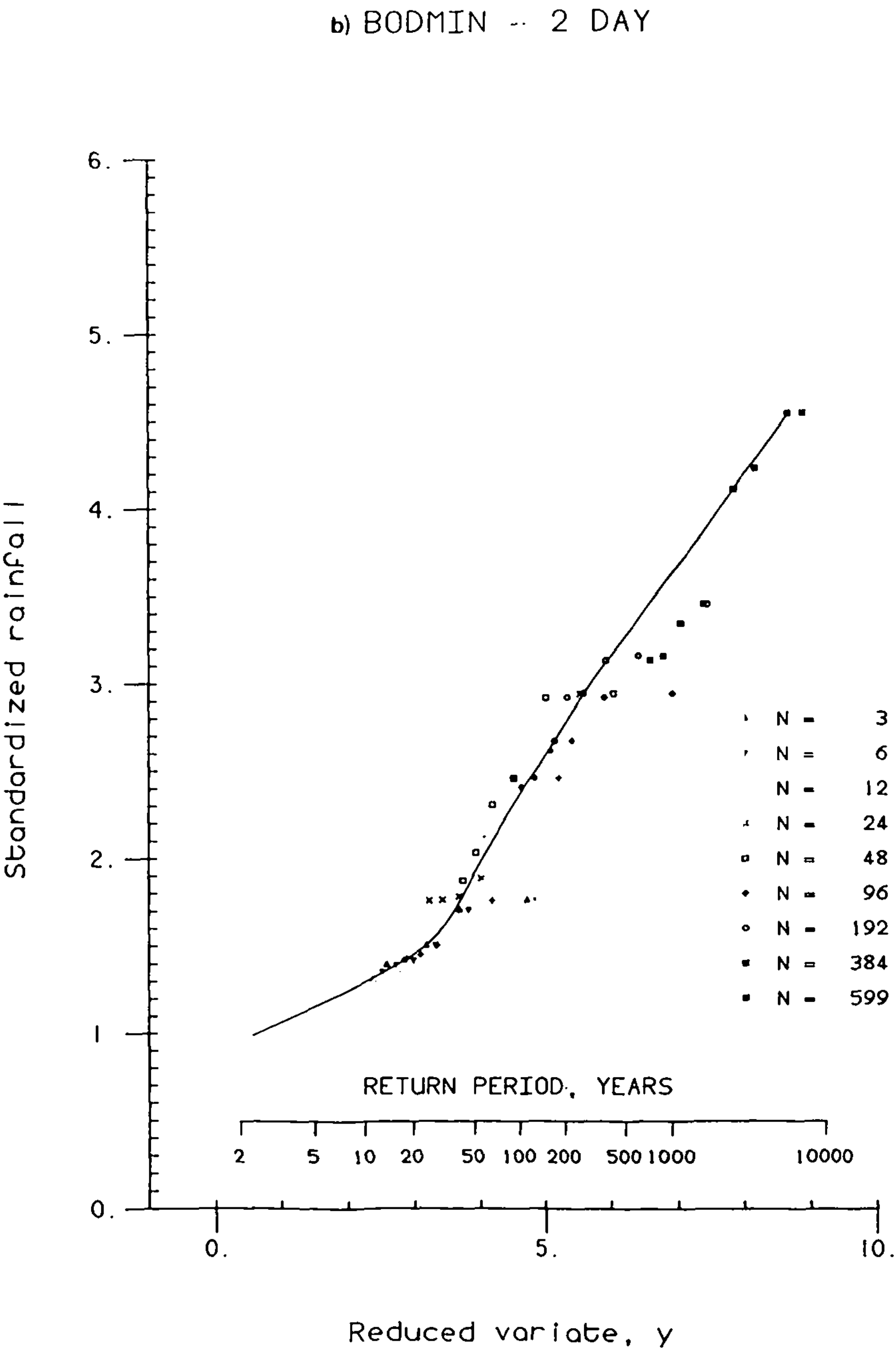


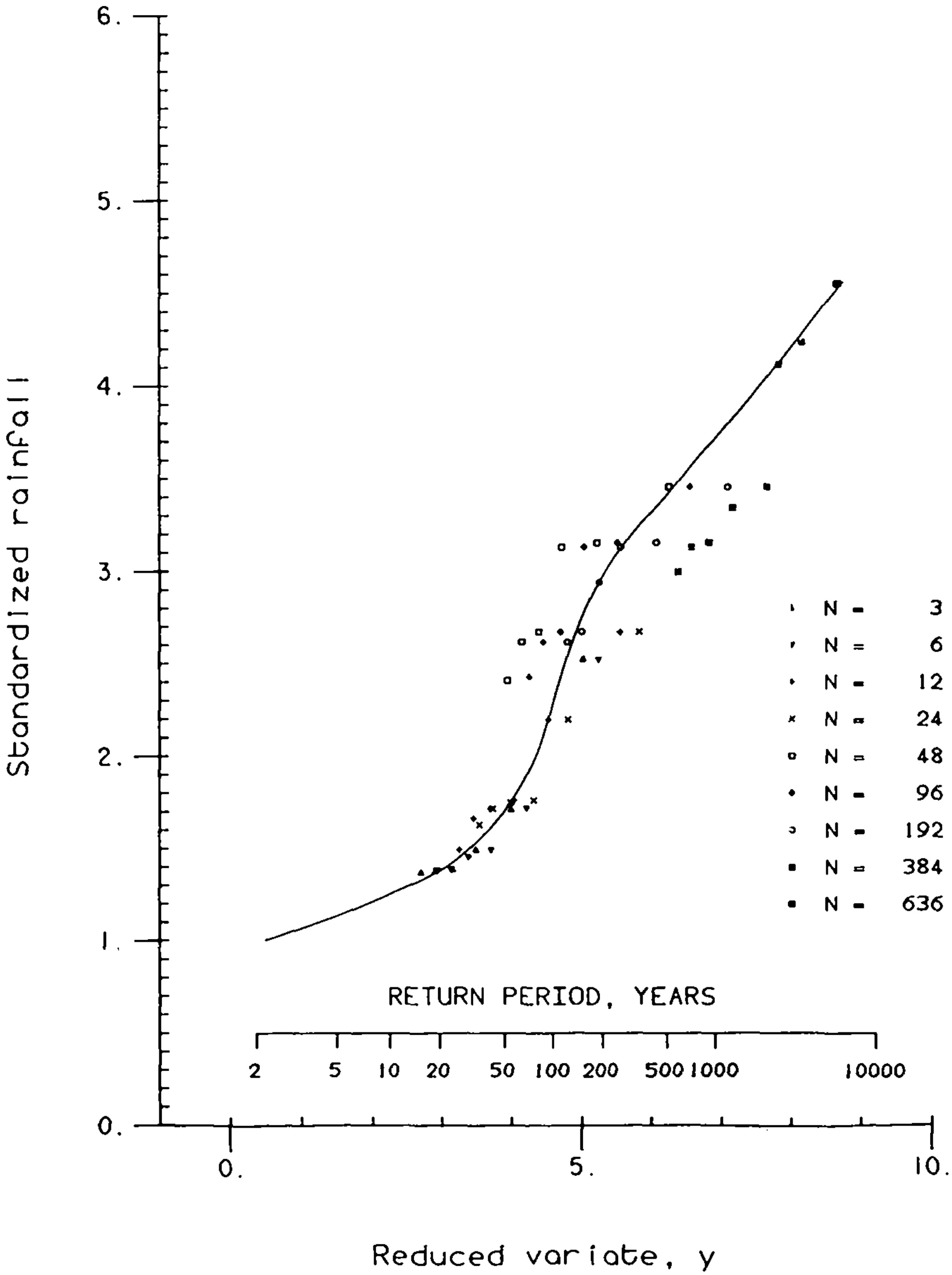
Figure 9 *2-day focussed growth curves for South West England:*

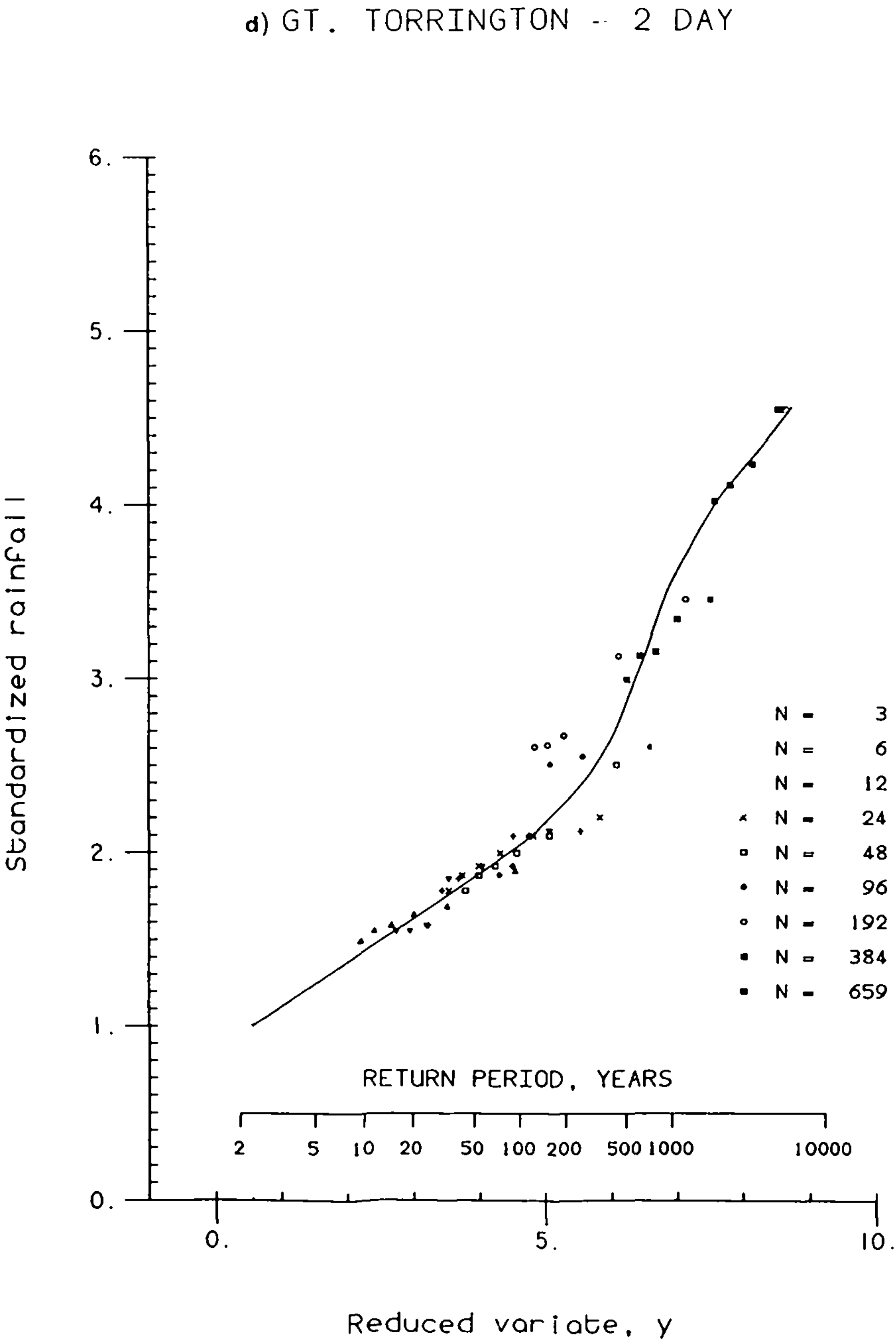
a) *Truro*
b) *Bodmin*
c) *Plymouth*
d) *Great Torrington*
e) *Exeter*
f) *Wimbleball*
g) *Bridgewater*
h) *Chard*
i) *Bristol*
j) *Dorchester*


a) TRURO -- 2 DAY
Standardized rainfall
Reduced variate, y
RETURN PERIOD, YEARS
2 5 10 20 50 100 200 500 1000 10000
0. 5. 10.
0. 1. 2. 3. 4. 5. 6.
N = 3
N = 6
N = 12
N = 24
N = 48
N = 96
N = 192
N = 384
N = 543


b) BODMIN -- 2 DAY
Standardized rainfall
6.
5.
4.
3.
2.
1
0.
RETURN PERIOD, YEARS
2
5
10
20
50
100
200
500
1000
10000
0.
5.
10.
Reduced variate, y
N = 3
N = 6
N = 12
N = 24
N = 48
N = 96
N = 192
N = 384
N = 599

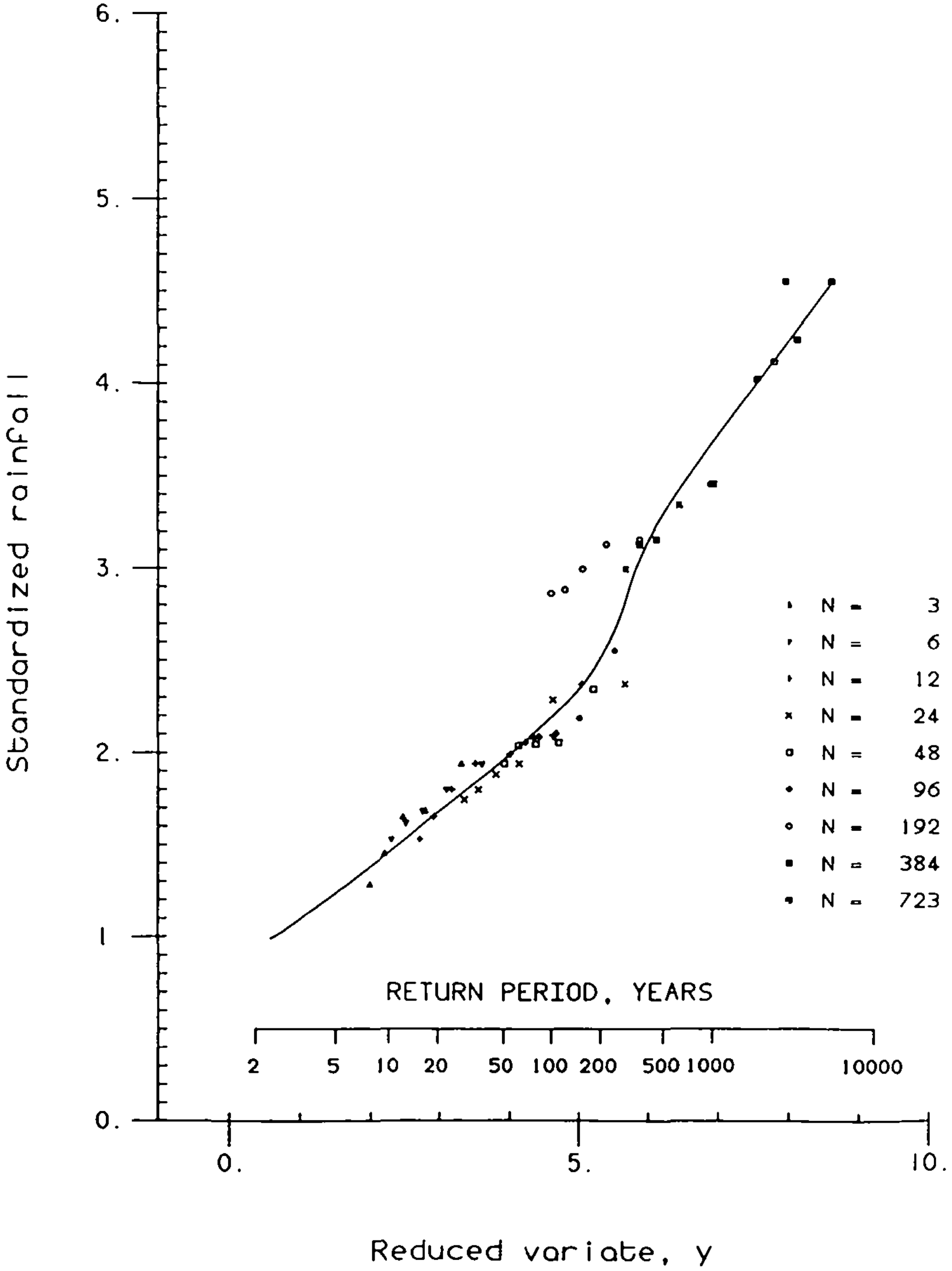
c) PLYMOUTH -- 2 DAY



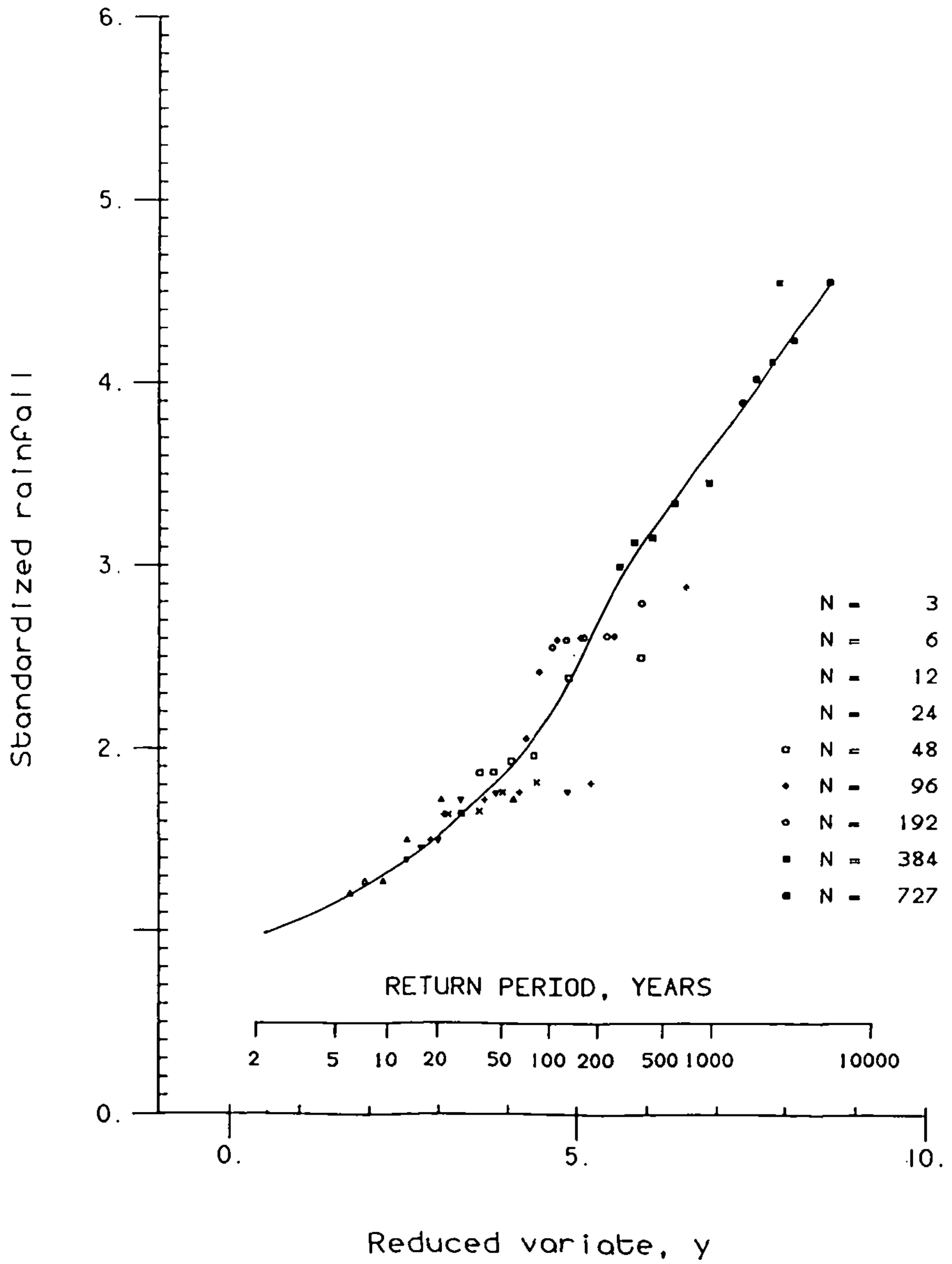


d) GT. TORRINGTON -- 2 DAY
Standardized rainfall
6.
5.
4.
3.
2.
1.
0.
N - 3
N = 6
N - 12
N - 24
N = 48
N - 96
N - 192
N = 384
N - 659
RETURN PERIOD, YEARS
2
5
10
20
50
100
200
500
1000
10000
0.
5.
10.
Reduced variate, y

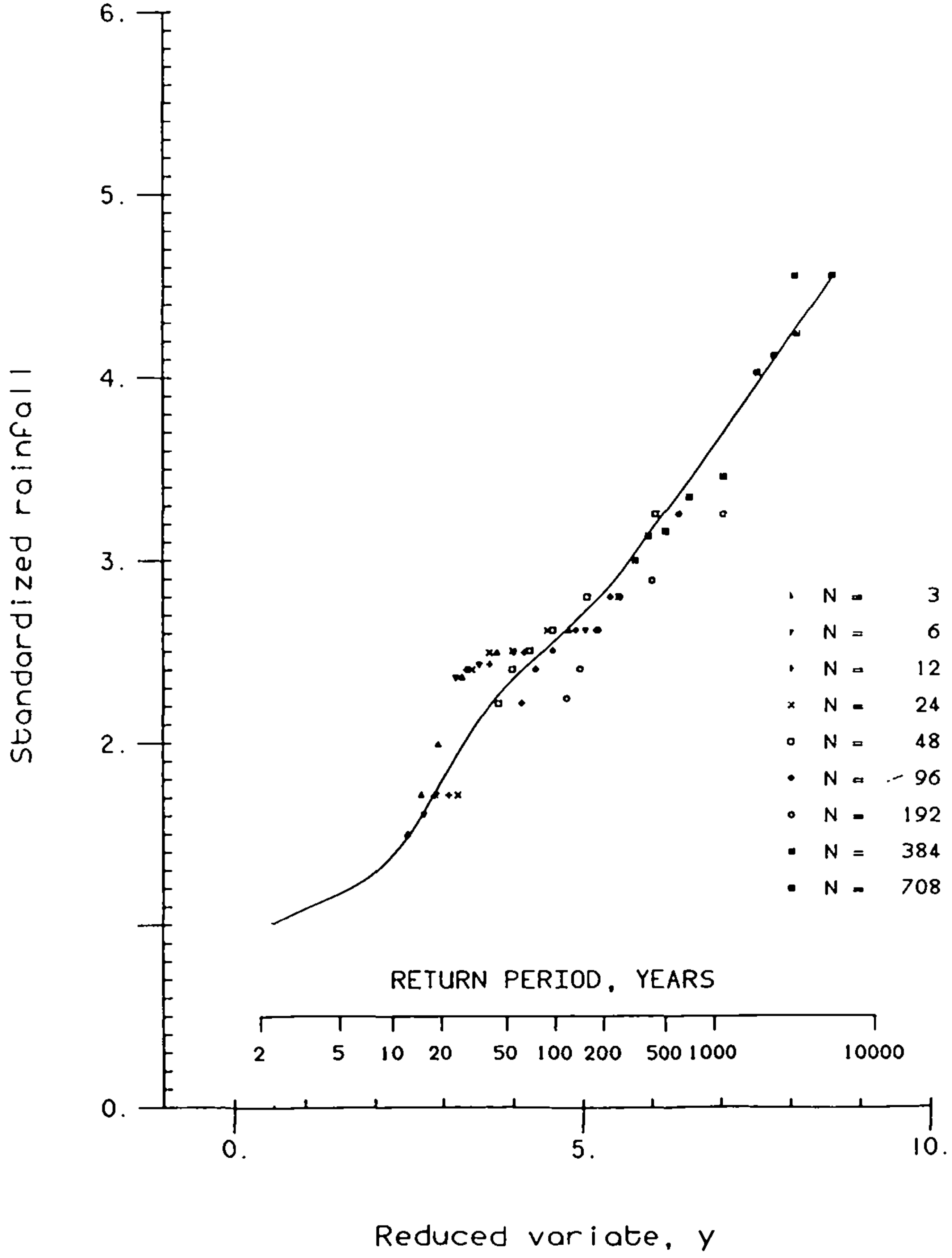
e) EXETER - 2 DAY



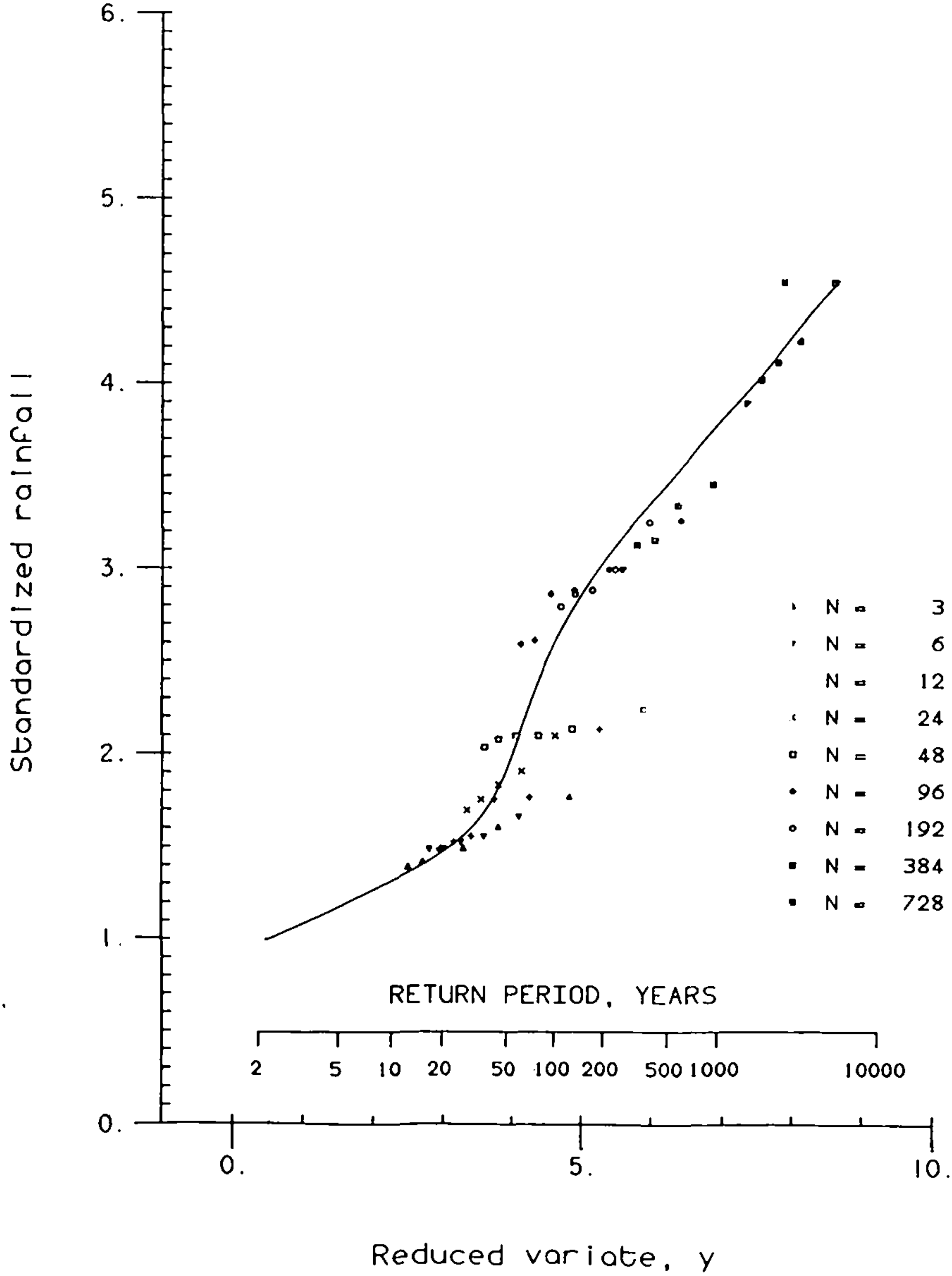
f) WIMBLEBALL 2 DAY



g) BRIDGWATER -- 2 DAY

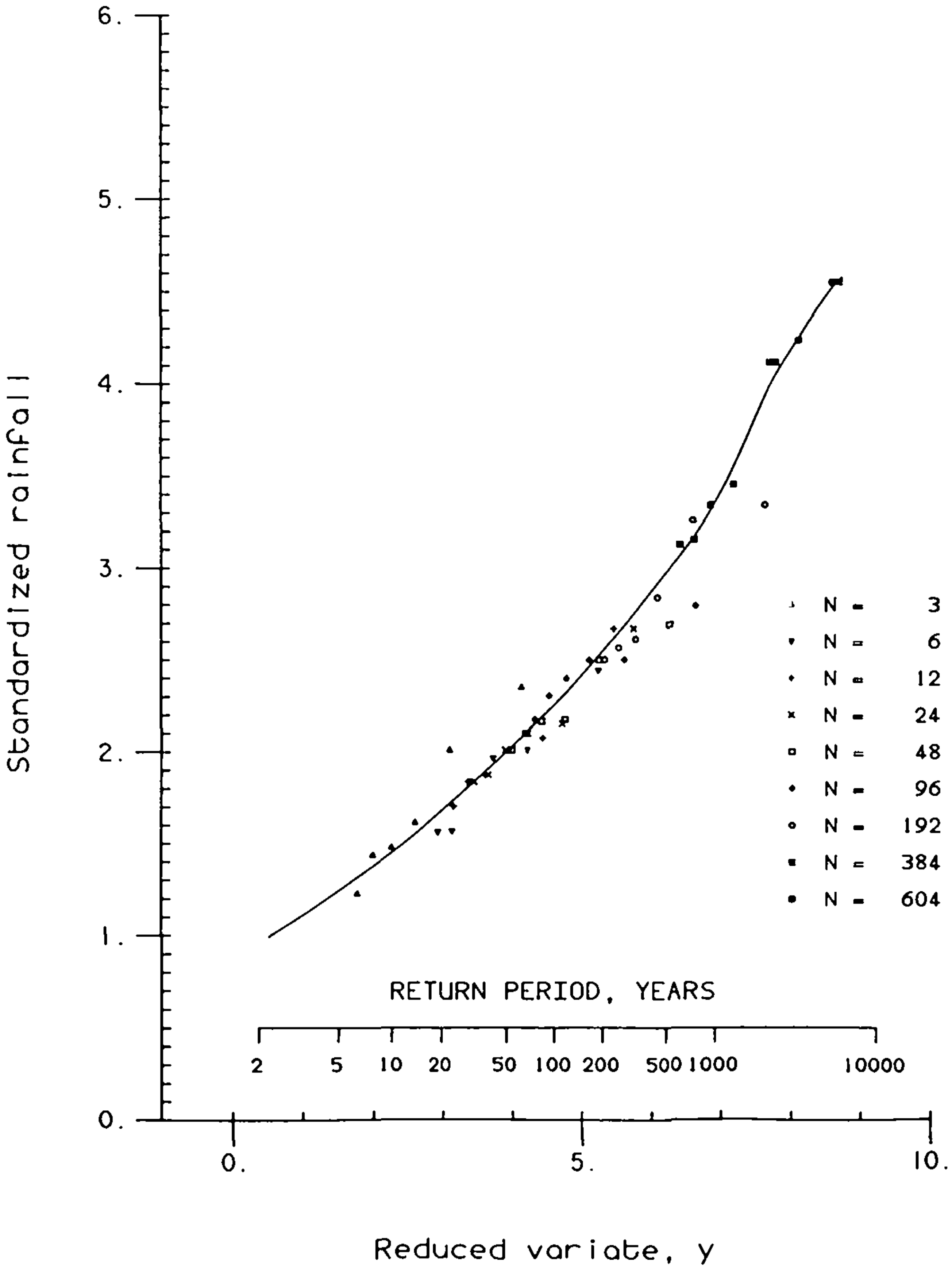


h) CHARD -- 2 DAY



6.
5.
4.
3.
2.
1.
0.
Standardized rainfall
N = 3
N = 6
N = 12
N = 24
N = 48
N = 96
N = 192
N = 384
N = 728
RETURN PERIOD, YEARS
2
5
10
20
50
100
200
500
1000
10000
0.
5.
10.
Reduced variate, y

i) BRISTOL 2 DAY



j) DORCHESTER 2 DAY

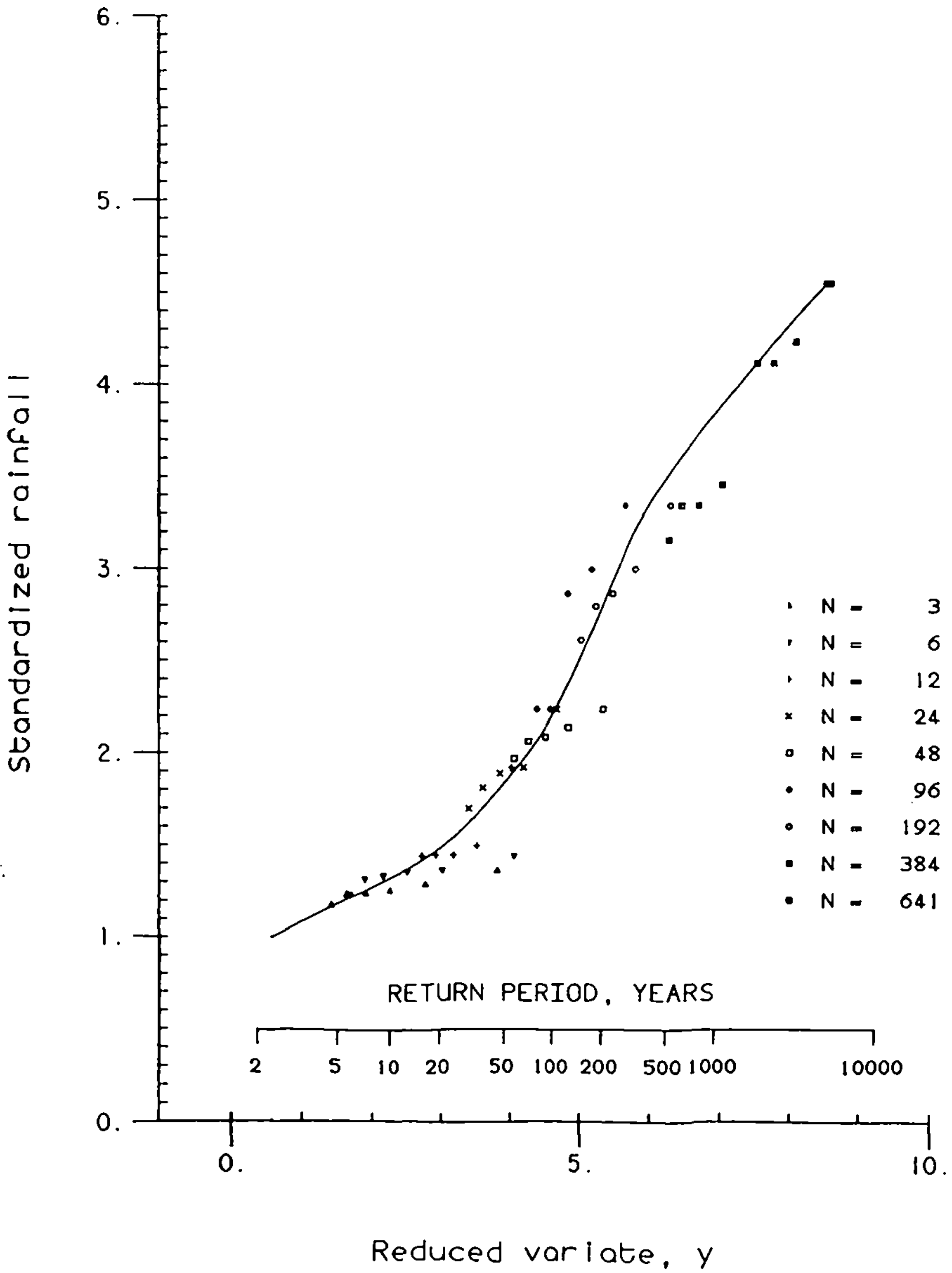


Figure 10 *Comparison of 1-day rainfall growth curves for South West England.*

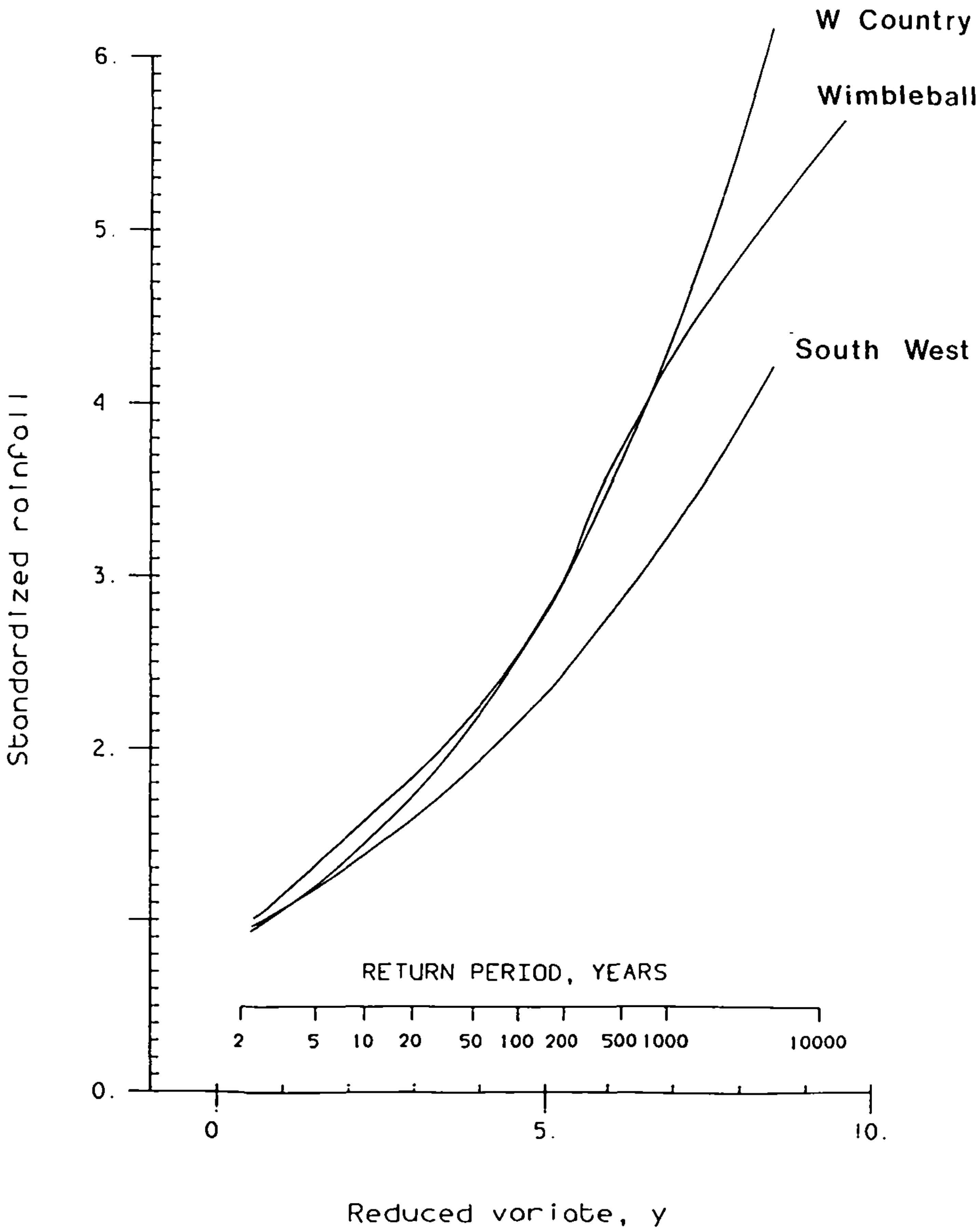


Figure 11 1-day rainfall frequency curves for Wimbleball Reservoir.

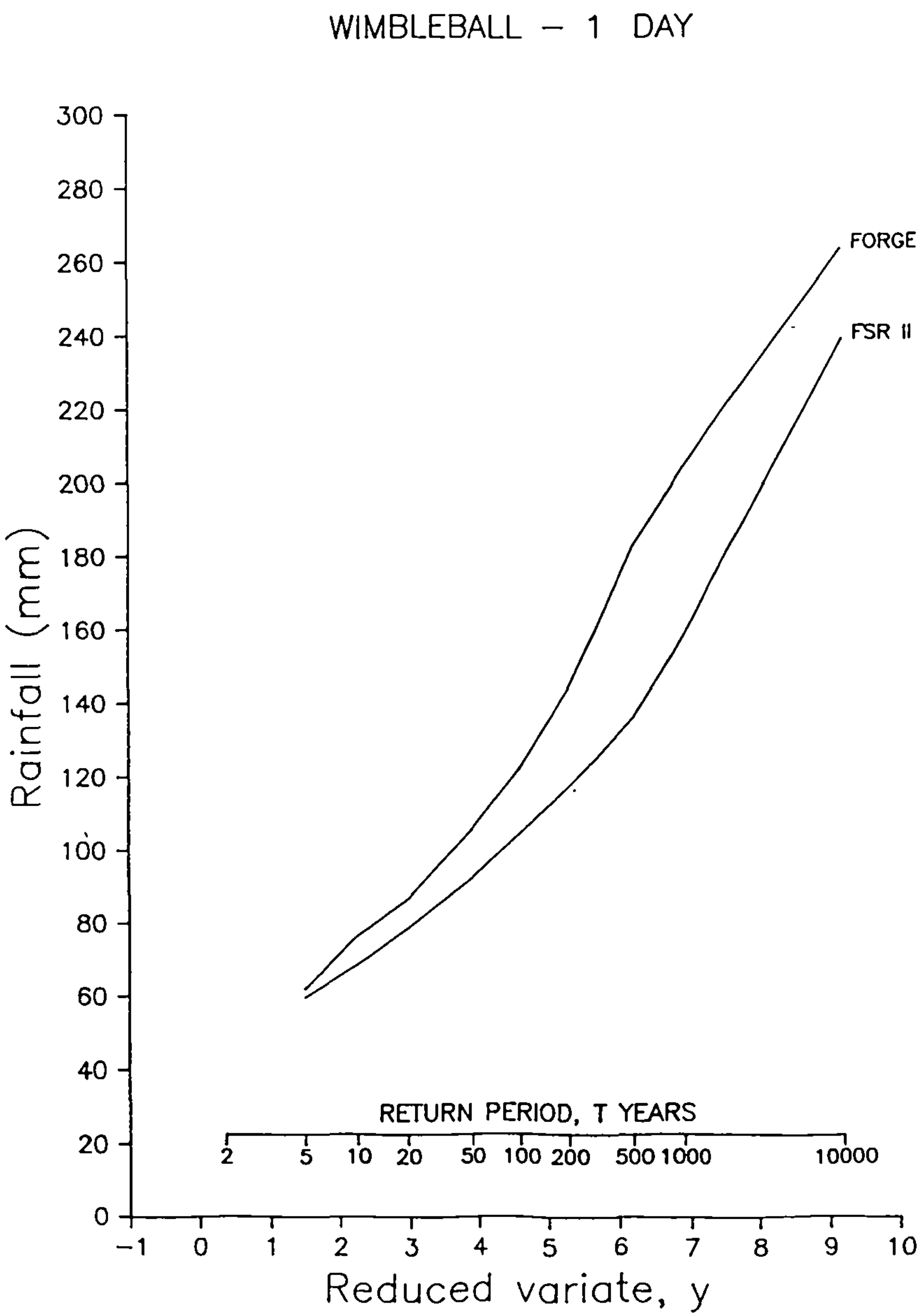


Figure 12   2-day rainfall frequency curves for Wimbleball Reservoir.

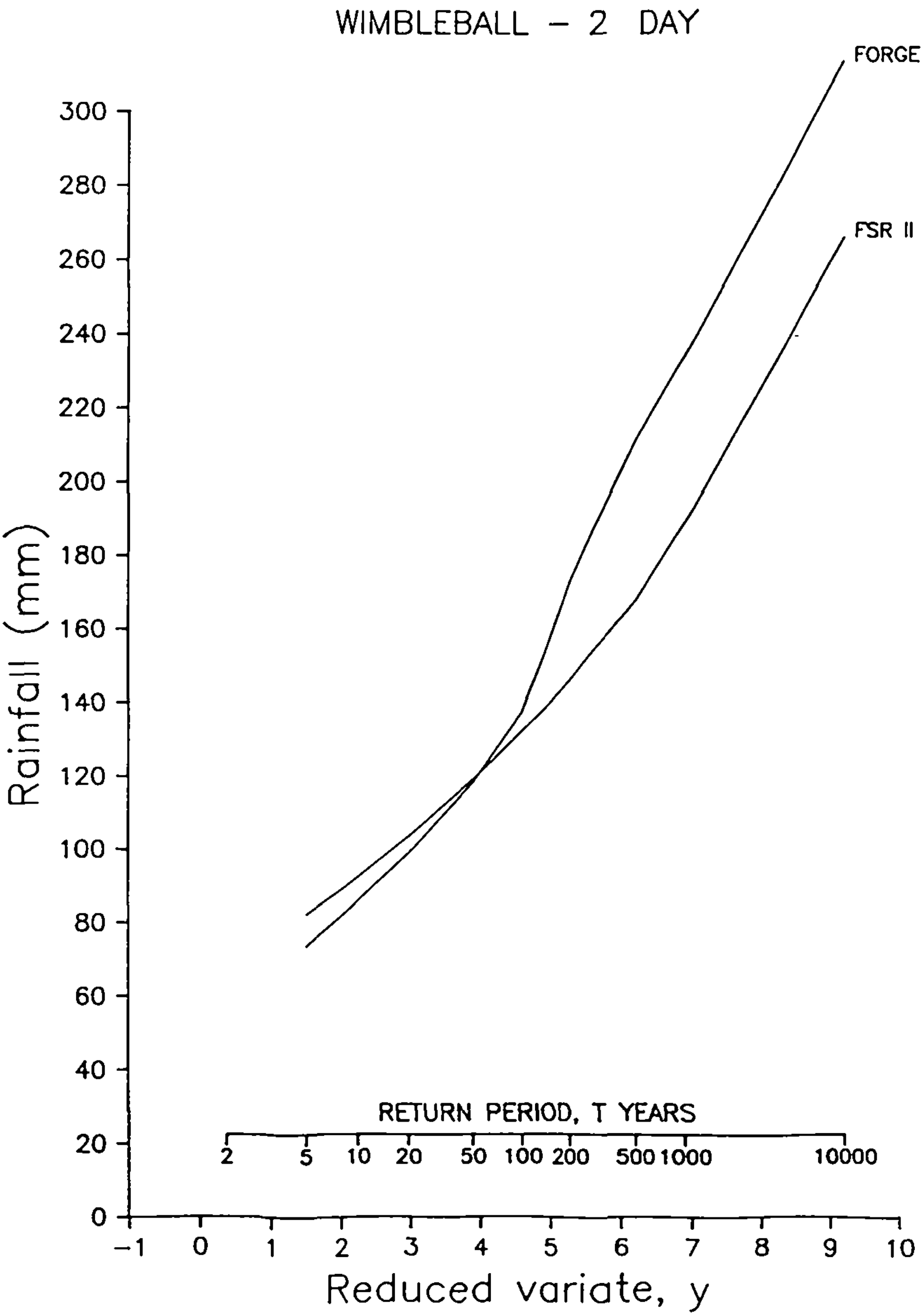


Figure 13   1-day rainfall frequency curves for Bridgwater.

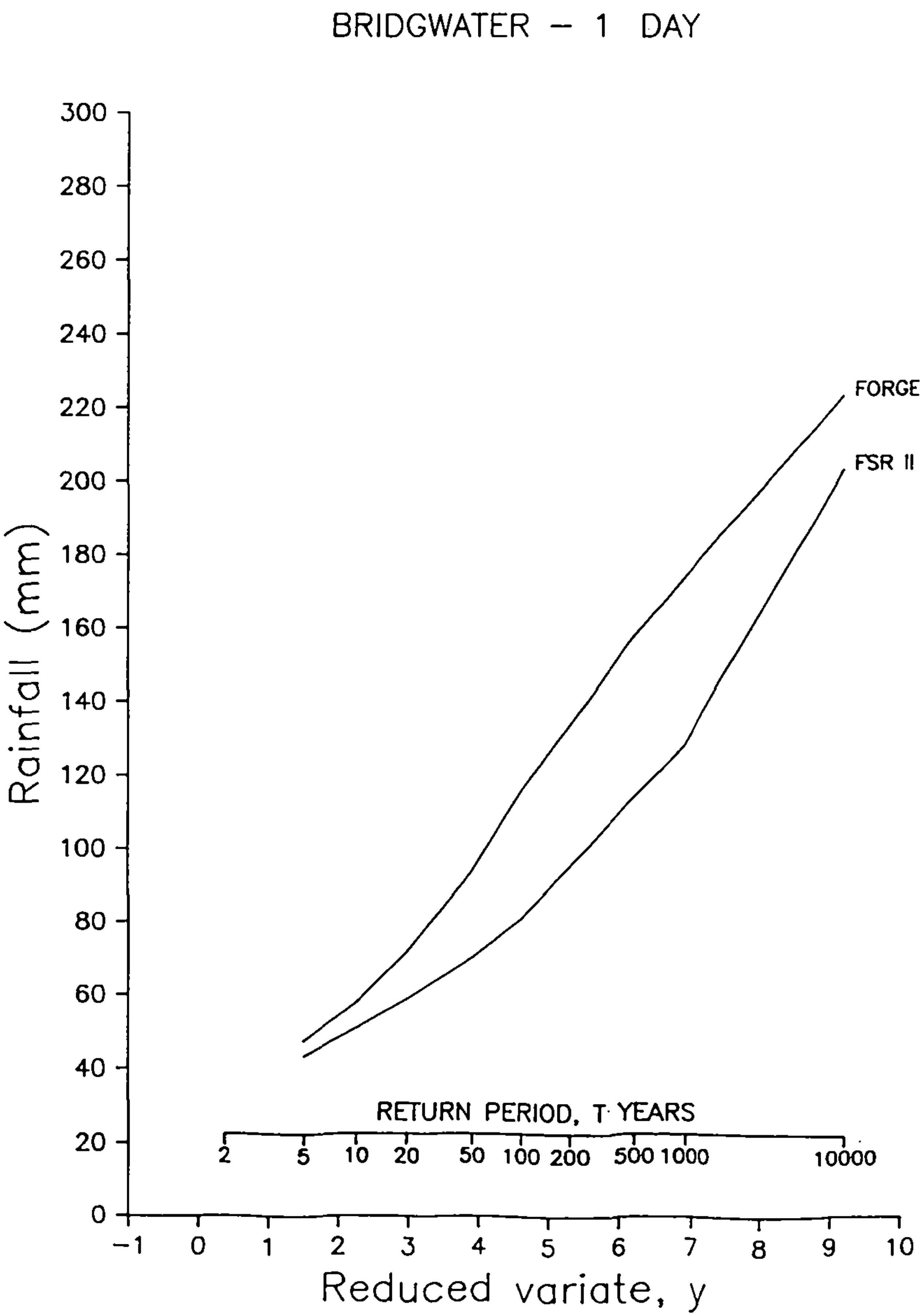
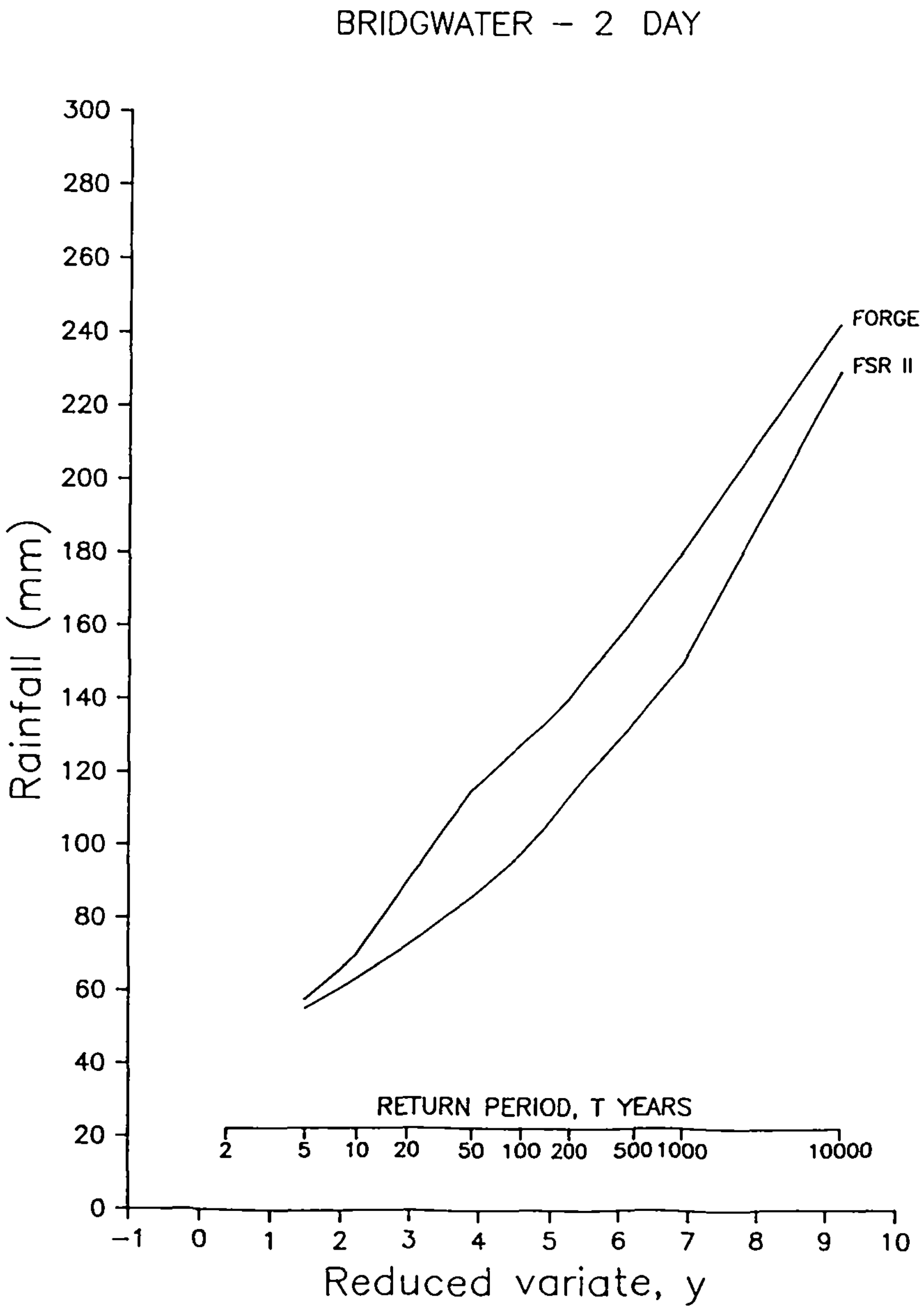


Figure 14   2-day rainfall frequency curves for Bridgwater.



Appendix 1 1 and 2-day rainfall statistics for gauges in the study region.

Gauge number	Grid reference		1-day RBAR(mm)	2-day RBAR(mm)	1-day CV(%)	2-day CV(%)	No. of years
346847	4045	950	35.81	48.32	22.03	25.14	26
346876	4060	924	37.12	48.83	23.15	22.78	26
346881	4074	923	37.86	49.98	25.62	23.98	21
346882	4082	919	36.97	49.19	23.76	25.57	16
346887	4077	926	35.04	44.16	29.54	19.59	10
346975	4016	903	36.17	48.37	21.88	23.65	21
347013	4006	937	36.36	49.35	27.87	25.35	24
347110	3876	928	38.05	50.77	23.17	21.82	15
347766	3805	1030	41.38	52.56	21.62	21.70	14
347819	3804	983	41.60	53.25	28.23	29.23	16
347927	3851	939	38.15	49.98	26.48	19.05	17
347973	3886	889	38.24	48.66	28.39	25.68	23
348392	3575	951	49.67	61.56	53.13	41.14	44
348684	3659	1040	45.66	56.35	22.84	22.14	26
348792	3667	949	43.94	57.35	25.02	25.96	12
348847	3684	905	41.29	53.30	16.15	16.85	26
348903	3716	928	37.24	49.99	21.81	17.08	14
348909	3712	917	40.08	53.61	22.68	19.68	15
348916	3718	912	42.46	54.00	27.14	20.85	24
349024	3648	888	43.74	55.95	25.13	17.88	17
349122	3688	898	39.88	53.69	20.46	18.34	20
349125	3693	899	40.19	53.25	17.25	19.46	10
349326	3741	878	41.15	52.70	23.59	21.54	15
349492	3820	870	40.71	54.18	29.62	25.09	24
349695	3870	866	42.50	53.84	27.07	23.72	18
349784	3911	823	41.75	54.64	33.58	31.90	63
350079	3960	825	42.02	55.16	32.07	28.87	19
350278	4030	794	34.67	47.35	25.18	18.94	26
350531	3707	839	41.96	51.56	17.40	22.00	10
350570	3681	805	37.27	48.14	33.79	26.92	11
350593	3652	857	42.93	53.05	63.40	49.78	67
350749	3661	795	38.18	47.02	35.33	25.99	17
350753	3676	791	36.64	46.07	58.11	46.39	68
350776	3677	692	35.28	44.88	26.62	29.91	18
350790	3687	717	39.11	50.55	30.91	28.41	15
350818	3667	770	31.31	43.68	22.45	20.65	10
350921	3578	852	37.56	46.75	29.98	28.93	26
351053	3550	902	42.22	51.35	23.34	24.89	17
351190	3482	1011	44.54	56.57	33.15	27.54	52
351256	3469	993	41.86	51.67	30.31	22.19	20
351463	3498	940	39.99	48.64	20.64	25.67	10
351827	3371	937	38.96	49.57	25.34	19.00	21
351986	3315	913	39.89	50.97	37.14	25.25	30
352001	3301	909	40.44	52.40	37.46	25.51	12
352281	3373	1086	45.80	60.80	28.85	24.91	48
352316	3359	1051	45.21	56.94	24.52	21.92	62
352461	3358	1006	45.79	58.16	29.57	26.26	17
352519	3291	1073	46.94	60.02	33.64	30.15	18
352634	3290	1037	41.04	52.77	27.22	29.37	10
352686	3307	977	43.47	54.72	29.76	26.63	20
352746	3271	1133	51.08	64.26	34.54	29.03	18
352856	3244	1082	42.91	55.08	43.78	43.23	12

Gauge number	Grid reference		1-day RBAR(mm)	2-day RBAR(mm)	1-day CV(%)	2-day CV(%)	No. of years
352861	3241	1079	50.96	57.68	46.83	36.14	10
353056	3267	986	39 33	50.30	27.12	23.48	33
353175	3259	926	40.35	46.24	39.93	32.53	11
353394	3207	1022	44.59	56.73	27.85	26.30	24
353419	3214	1004	44.16	57.29	23.89	29.10	14
353423	3210	1000	55.66	69.46	43.33	33.86	10
353472	3248	966	36.62	47.07	14.86	25.85	19
353510	3236	922	34.64	48.09	17.08	17.61	13
353518	3244	923	40.36	50.39	44.59	33.79	42
353529	3259	913	32.91	45.12	12.25	19.25	10
353608	3230	894	43.14	51.44	66.13	56.83	31
353612	3226	892	38.87	47.41	40.04	32.01	17
353863	3124	873	37.66	46.00	45.38	35.79	23
353894	3224	1141	47.79	66.31	22.89	27.87	16
353964	3206	1089	47.88	61.51	44.51	33.72	15
353967	3203	1088	42.62	55.47	31.48	34.54	12
354170	3171	1004	48.64	62.00	35.37	30.76	28
354295	3108	994	38.01	49.78	27.58	23.38	56
354352	3101	1048	41.18	50.34	64.32	51.17	17
354492	3110	954	41.53	54.36	34.06	24.50	25
354497	3088	952	40.93	49.04	51.46	42.86	15
354556	3071	928	39.27	48.04	22.45	19.92	32
354568	3067	921	43.23	52.97	40.33	29.22	12
354590	3084	914	38.86	47.70	31.68	24.13	16
354658	3082	882	39.34	48.86	37.51	30.10	23
354778	3064	830	34.52	44.71	21.54	20.81	16
354864	3026	819	38.09	46.82	34.27	28.55	77
354880	3015	813	40.23	49.35	38.68	30.73	26
354895	3013	825	36.34	47.70	26.60	23.19	15
355052	3021	1005	37.94	47.04	46.84	35.47	21
355279	3031	939	39.67	49.77	38.14	27.04	54
355348	2964	940	42.39	50.11	45.64	37.31	18
355363	3001	933	40.51	50.86	44.18	31.64	26
355436	2970	934	41.13	49.94	37.21	32.62	27
355459	3039	892	40.90	52.36	31.98	24.88	19
355639	2843	1383	65.39	85.27	29.25	26.01	38
355650	2857	1384	58.30	77.74	19.90	22.31	23
355735	2906	1348	51.91	67.91	28.14	21.65	45
356081	2961	1338	52.39	71.87	26.08	16.85	16
356232	2784	1389	66.20	82.14	19.29	14.35	11
356262	2797	1392	57.52	78.52	41.34	31.97	44
356466	2877	1327	52.60	69.39	16.62	19.53	26
356616	2912	1280	48.55	60.07	39.32	29.91	22
356650	2930	1243	45.30	56.28	22.50	16.01	12
356671	2875	1266	40.43	54.09	30.70	25.07	24
356984	3022	1230	40.46	51.71	38.07	28.13	23
357054	2966	1255	44.21	57.08	34.41	26.11	31
357055	2964	1256	42.71	56.09	40.10	27.86	16
357187	2916	1185	46.71	55.27	50.47	36.86	11
357205	2928	1171	37.62	50.82	12.85	13.63	13
357435	2990	1180	38.84	49.83	37.68	26.79	22
357477	2965	1132	36.62	48.62	29.20	24.09	34

Gauge number	Grid reference		1-day RBAR(mm)	2-day RBAR(mm)	1-day CV(%)	2-day CV(%)	No. of years
357522	2966	1152	34.26	45.41	16.31	18.16	10
357703	2914	1080	31.16	44.09	12.06	22.47	10
357958	2925	984	37.39	49.35	36.72	24.72	16
357960	2936	981	35.38	47.81	39.59	28.16	16
357983	3202	1162	53.79	65.07	42.30	32.71	17
358100	3136	1076	42.33	52.64	19.90	15.32	21
358232	3139	1126	46.49	59.85	43.24	35.77	22
358233	3139	1128	47.04	58.17	46.23	35.34	12
358263	3122	1147	43.22	55.32	47.34	36.81	17
358300	3102	1152	37.67	48.69	39.88	32.85	44
358511	3065	1075	37.70	48.52	47.20	34.16	23
358549	3039	1194	45.86	54.69	49.49	37.81	11
358550	3041	1195	36.07	48.20	19.37	15.82	11
358670	3033	1113	39.86	50.99	50.62	37.11	14
358674	3035	1103	34.59	43.95	23.01	19.71	15
358795	3020	1073	35.74	46.87	33.42	25.38	72
358856	3000	1045	35.97	44.45	30.43	25.21	52
358942	2994	1033	40.80	49.53	41.27	35.49	25
359171	2819	1074	37.94	47.32	42.45	29.79	22
359424	2726	943	39.23	54.95	27.42	28.95	12
359600	2760	1003	40.55	50.52	44.46	34.38	13
359631	2771	1020	35.21	45.39	32.00	24.47	48
359725	2805	1014	34.04	45.31	43.00	33.63	20
359869	2832	1006	35.25	45.34	46.21	34.20	13
359946	2861	1011	39.65	47.58	38.95	31.43	19
359975	2879	981	41.84	51.16	37.30	27.23	18
360143	2921	926	43.40	51.54	38.61	32.73	14
360155	2928	917	35.11	49.22	17.58	24.00	16
360199	2943	920	38.94	48.94	37.25	33.67	38
360247	2894	917	41.49	55.91	39.87	34.14	18
360333	2905	880	41.90	52.74	32.99	35.17	38
360344	2926	889	41.07	52.38	28.60	32.11	33
360699	2957	836	37.66	52.32	21.44	30.84	16
360709	2959	834	37.96	47.35	32.06	29.18	29
360724	2972	821	38.35	48.79	35.35	28.47	26
360763	2944	800	43.46	56.29	39.44	32.31	21
360863	2943	768	41.88	54.10	29.22	27.38	45
360892	2953	751	40.52	51.71	33.89	26.42	26
360901	2941	745	43.52	56.62	31.99	25.46	17
360905	2938	737	37.95	48.46	15.41	19.21	14
360906	2941	728	38.31	47.68	31.68	28.45	77
361067	2674	894	46.77	63.86	21.40	29.53	14
361121	2670	842	67.38	89.49	31.32	26.97	30
361123	2672	843	70.45	93.62	25.11	26.68	30
361126	2673	842	71.76	93.39	17.84	29.45	14
361130	2670	850	64.54	88.25	33.01	25.83	56
361155	2692	881	56.62	68.96	43.15	31.64	11
361185	2714	870	55.12	71.51	30.15	28.19	24
361273	2711	921	42.48	57.68	50.65	38.64	25
361321	2770	932	39.90	58.01	19.27	26.22	13
361361	2775	908	45.96	61.96	17.71	28.69	11
361704	2807	839	46.35	60.22	26.85	23.73	66

Gauge number	Grid reference		1-day RBAR(mm)	2-day RBAR(mm)	1-day CV(%)	2-day CV(%)	No. of years
361706	2808	838	52.25	70.92	34.80	38.95	23
361710	2807	823	48.83	65.57	32.06	33.37	27
361732	2855	821	40.90	58.66	33.84	45.87	15
361737	2830	805	45.12	57.53	41.86	29.98	32
361753	2884	847	47.14	65.66	34.20	32.83	18
361850	2866	793	43.45	57.78	30.79	32.36	25
361997	2752	841	55.38	71.14	28.05	24.02	11
362061	2727	807	66.67	82.57	34.85	28.48	12
362187	2786	783	53.49	72.34	32.76	36.86	21
362194	2786	792	56.16	75.15	29.77	32.19	11
362248	2800	770	59.55	80.52	40.59	40.84	11
362452	2828	729	44.36	57.32	37.19	30.58	20
362732	2862	652	45.29	60.35	29.76	25.70	23
362836	2899	744	36.40	53.67	19.51	30.78	11
362891	2927	713	41.09	52.33	27.82	21.32	43
362910	2935	745	39.57	50.82	33.06	28.22	48
363007	2927	646	39.60	50.92	33.93	25.26	22
363036	2909	638	38.41	50.95	27.53	23.32	31
363095	2890	609	37.72	53.21	29.77	21.22	18
363157	2927	556	41.87	54.72	26.68	22.00	19
363294	2653	787	58.76	78.56	32.99	25.30	13
363474	2586	741	85.30	110.29	63.63	48.50	65
363534	2622	760	65.01	84.18	16.49	22.02	13
363595	2620	704	66.27	93.91	21.52	24.16	35
363624	2633	719	74.39	98.62	24.86	31.44	25
363697	2684	707	74.44	97.94	23.46	26.33	58
363700	2688	711	70.13	93.64	24.62	27.68	59
363871	2718	767	58.13	76.00	30.38	33.68	18
363949	2743	703	47.39	64.25	19.78	25.54	14
364046	2756	695	62.47	81.26	36.09	30.27	30
364119	2723	643	58.00	84.01	16.34	29.86	13
364177	2749	659	54.35	72.98	30.71	33.82	20
364283	2744	605	50.01	68.46	14.15	25.90	16
364314	2788	620	46.74	63.25	28.90	28.23	38
364375	2804	660	45.09	59.90	42.17	38.67	36
365046	2879	515	44.68	58.86	22.05	23.37	48
365057	2886	512	44.30	57.65	30.37	16.65	10
365060	2880	505	42.64	56.87	25.63	25.28	52
365364	2824	449	43.00	56.17	28.75	18.54	26
365772	2678	398	35.21	48.44	26.00	31.40	16
365789	2725	427	42.81	53.82	31.62	28.06	14
365962	2679	649	74.91	101.55	20.16	23.52	30
365974	2691	628	64.62	89.41	22.14	24.07	22
365998	2671	629	80.65	105.47	27.09	29.36	10
365999	2675	627	69.53	95.04	18.80	22.21	33
366012	2685	617	71.14	91.80	52.00	40.37	42
366105	2712	576	50.55	70.75	30.05	24.96	23
366134	2732	558	47.90	64.51	28.11	25.26	21
366223	2727	522	46.09	62.92	23.66	24.64	33
366467	2661	446	41.12	50.19	28.79	22.92	19
366619	2638	590	49.20	71.29	13.14	22.78	12
366705	2666	575	49.14	65.82	23.21	21.19	61

Gauge number	Grid reference		1-day RBAR(mm)	2-day RBAR(mm)	1-day CV(%)	2-day CV(%)	No. of years
366873	2667	502	38.90	52.66	20.40	22.72	14
368060	2629	612	57.33	75.39	25.49	22.74	21
368119	2588	590	46.06	64.51	19.83	25.42	12
368124	2598	585	48.57	65.06	34.87	24.15	19
368231	2577	512	39.54	52.08	23.80	19.49	38
368235	2574	504	38.86	51.14	21.06	25.09	11
368487	2492	529	40.00	51.62	34.51	26.11	56
368633	2585	735	61.17	79.99	28.36	29.02	35
368668	2566	698	49.35	66.10	25.25	18.02	13
368714	2553	687	53.96	67.90	26.70	25.27	26
368715	2552	685	55.34	68.95	26.63	25.07	23
368717	2558	682	55.64	73.63	22.60	21.25	60
368923	2574	628	52.74	69.73	28.05	22.67	41
369021	2531	571	43.49	55.89	37.84	29.08	30
369051	2486	569	42.16	55.54	46.97	34.42	19
369122	2478	537	37.84	48.12	33.91	27.33	81
369124	2481	551	41.99	53.32	46.97	32.87	17
369296	2474	640	51.17	65.72	34.52	28.80	55
369483	2522	813	55.89	71.77	17.72	33.39	12
369503	2509	784	54.18	69.06	21.26	30.23	12
369680	2482	748	49.41	61.56	58.18	36.94	93
369919	2577	742	60.01	77.30	38.72	40.34	23
370007	2512	701	51.71	64.90	44.60	30.01	22
370096	2513	675	49.84	64.77	43.36	34.20	20
370542	2311	1021	41.28	50.94	40.04	33.69	26
370543	2312	1028	36.75	47.93	28.43	29.49	10
370579	2314	982	37.62	49.07	33.24	29.09	60
370612	2327	1066	40.24	50.02	20.87	25.28	12
370670	2365	1058	43.06	54.85	39.38	27.44	18
370679	2343	1040	39.29	52.03	27.88	22.76	34
370934	2309	947	43.88	54.25	38.89	31.00	28
371160	2169	916	37.27	52.63	26.15	19.79	12
371322	2227	916	40.68	57.38	20.91	31.98	12
371460	2259	901	42.71	59.07	41.24	31.00	18
371600	2332	872	41.41	55.10	30.81	27.22	30
371634	2413	1013	37.02	52.12	23.93	22.02	12
371724	2388	952	41.12	50.74	35.75	30.45	16
371799	2379	926	38.12	50.96	41.09	39.00	10
371899	2230	869	45.68	65.27	19.73	27.95	12
372003	2327	839	45.51	60.33	36.12	32.38	26
372159	2548	910	54.21	71.14	30.25	25.75	26
372318	2473	848	46.81	60.88	30.87	24.44	58
372437	2397	849	43.43	56.53	22.95	33.96	10
372697	2462	950	33.39	47.53	24.01	34.65	11
372920	2396	819	42.77	56.34	19.26	30.33	12
373078	2349	797	40.69	54.63	29.35	24.48	84
373165	2222	812	54.57	75.16	22.09	26.43	12
373392	2286	803	50.51	-	50.78	-	10
373827	2422	707	48.59	61.87	41.92	30.06	13
373953	2406	647	47.07	59.54	44.88	34.11	23
374086	2401	632	44.76	54.57	56.11	40.68	20
374093	2435	626	43.98	54.44	17.04	16.71	10

Gauge number	Grid reference		1-day RBAR(mm)	2-day RBAR(mm)	1-day CV(%)	2-day CV(%)	No. of years
374322	2244	765	54.11	75.00	29.18	26.28	25
374323	2244	765	46.86	62.34	17.17	17.06	17
374360	2295	770	47.78	63.35	16.60	23.61	12
374385	2289	743	46.37	62.69	18.08	28.04	12
374499	2273	707	56.64	74.61	27.97	25.50	21
374514	2290	701	52.72	69.63	35.79	27.46	19
374661	2323	741	46.28	61.47	18.46	20.21	12
375292	2253	675	50.00	66.34	29.97	24.39	24
375396	2282	596	46.42	58.09	21.43	18.44	17
375568	2240	630	44.63	61.72	19.39	23.48	10
375572	2257	642	47.51	60.32	40.14	25.43	13
375746	2209	613	46.68	62.82	35.06	32.79	23
376507	2167	707	47.47	67.86	19.62	22.16	12
376747	2096	624	45.03	61.29	17.11	29.51	13
376770	2107	600	43.73	63.17	20.48	27.43	10
377089	2121	520	37.01	49.17	24.58	21.38	17
377162	1989	606	47.35	62.83	22.96	23.72	15
377222	2015	587	53.48	72.31	21.97	22.19	11
377449	2041	532	41.61	51.29	28.16	21.77	11
377504	2002	559	50.04	65.93	19.70	17.78	11
377557	2018	525	46.47	60.90	44.45	33.95	19
377795	1978	468	41.16	51.24	25.12	23.01	11
378025	1851	350	40.57	53.19	43.35	35.93	12
378032	1853	330	38.52	49.26	37.13	30.50	35
378296	1966	527	49.88	-	24.71	-	10
378299	1966	518	49.64	63.26	44.97	34.68	18
378760	1834	456	43.98	55.84	39.74	34.09	20
378768	1831	435	40.57	53.57	38.06	41.64	11
378965	1891	511	43.62	55.23	36.67	32.93	29
379134	1847	464	43.46	55.36	32.58	28.98	82
379372	1736	402	44.53	57.51	30.53	26.41	97
379495	1722	365	51.87	66.85	32.60	32.19	13
379706	1778	336	45.49	57.46	40.95	32.22	26
379710	1784	341	46.11	58.54	29.56	26.02	16
379758	1802	325	41.59	52.47	33.45	23.77	89
379919	1677	307	49.85	60.37	51.14	42.96	29
380002	1722	214	52.96	64.35	40.57	42.27	11
380483	1700	119	36.98	48.98	41.77	30.81	25
380837	1676	253	44.59	52.89	39.09	29.69	16
380967	1516	300	38.54	49.13	34.56	32.74	23
381117	1486	317	41.37	52.67	35.21	27.71	21
381210	1469	302	39.42	51.04	28.48	24.91	91
381232	1450	313	47.11	59.63	30.88	32.49	26
381316	1437	286	44.94	57.26	33.81	32.94	25
381319	1442	295	45.96	58.02	34.83	33.15	26
381518	1385	227	39.01	48.84	29.30	26.66	30
381548	1365	217	33.08	42.36	26.29	27.29	14
381584	913	121	35.64	47.10	28.91	26.25	70
381899	1501	392	47.06	60.66	38.04	31.15	28
382035	1581	325	40.23	50.66	22.26	23.49	12
382153	1543	359	41.42	52.00	32.65	28.41	23
382380	1643	412	42.54	54.63	35.80	31.96	26

Gauge number	Grid reference		1-day RBAR(mm)	2-day RBAR(mm)	1-day CV(%)	2-day CV(%)	No. of years
382444	1657	363	47.68	60.71	32.23	31.11	35
382603	1703	459	40.57	52.23	36.36	40.92	12
382793	1721	505	46.36	58.34	50.70	39.00	29
382923	1787	537	46.36	60.28	42.90	38.16	12
383335	1801	604	40.62	50.87	43.67	34.64	16
383351	1812	614	35.91	44.77	41.36	34.20	71
383478	1873	642	40.61	52.31	46.23	34.87	30
383584	1910	638	42.50	56.95	21.44	15.07	10
383815	1867	745	36.05	46.48	37.37	26.55	26
383874	1889	759	37.37	44.80	42.55	34.07	28
383900	1914	755	33.70	44.17	40.58	32.53	12
383902	1917	754	36.15	47.43	32.85	23.43	20
384021	1978	729	46.49	58.75	70.04	50.67	12
384073	2104	832	56.38	70.13	62.62	47.21	28
384101	2128	831	54.77	71.69	40.64	35.30	34
384158	2126	807	47.88	65.40	26.95	26.38	25
384342	2132	765	48.45	65.79	25.20	22.13	26
384541	2076	673	44.73	57.95	27.83	24.70	46
384542	2073	672	43.22	60.02	18.83	25.12	10
384895	2075	835	53.36	62.72	58.19	52.75	18
384966	2075	785	40.22	55.65	21.28	25.49	12
385207	1982	727	34.85	46.62	39.70	37.38	14
385436	1937	772	32.47	43.05	46.85	31.88	10
385503	1990	789	39.52	50.15	55.92	40.87	13
385633	2064	889	38.95	49.02	35.00	29.41	29
385637	2092	866	45.87	56.83	33.76	28.88	18
385701	2130	902	43.26	57.32	29.50	36.52	12
386255	2208	1063	33.48	43.29	27.97	25.97	74
387198	2231	1276	33.18	43.38	28.12	26.81	26
387253	2310	1250	43.12	55.86	27.88	20.70	36
387321	2443	1297	33.08	41.51	35.85	25.80	17
387585	2337	1163	44.71	59.74	21.20	27.93	14
387598	2367	1163	39.40	53.17	20.26	24.48	13
387698	2394	1118	48.98	61.91	30.00	27.53	23
387787	2447	1094	41.11	51.78	41.36	34.15	23
388371	2483	962	47.15	59.76	38.16	31.09	22
388389	2507	940	44.67	59.44	16.52	31.43	10
388514	2445	1016	39.20	50.17	44.49	32.75	21
388667	2547	978	38.85	53.26	12.87	18.48	16
388772	2499	1048	42.46	52.43	52.91	41.20	12
388933	2585	928	56.00	74.53	33.49	29.25	23
388936	2587	938	50.87	66.88	38.48	28.06	34
389005	2615	934	57.07	76.61	22.86	29.00	18
389018	2591	946	47.26	64.20	37.95	29.33	25
389191	2610	1015	34.93	45.79	52.57	39.51	21
389284	2612	1069	41.03	50.19	57.52	44.46	12
389394	2563	1080	37.33	48.38	13.45	16.68	10
389623	2507	1102	39.57	51.64	17.71	15.60	12
389716	2579	1171	37.34	48.08	41.56	30.20	22
389897	2482	1191	39.10	50.03	34.87	29.02	23
390167	2387	1202	46.06	60.70	29.86	25.86	87
390388	2444	1247	36.24	47.42	34.73	29.10	60

Gauge number	Grid reference	1-day RBAR(mm)	2-day RBAR(mm)	1-day CV(%)	2-day CV(%)	No. of years
390467	2483 1253	37.52	48.54	39.48	28.56	30
390468	2483 1253	37.00	48.24	38.78	29.35	50
390480	2454 1271	39.12	47.65	31.44	30.67	20
390516	2448 1277	37.76	46.15	36.69	37.39	14
390858	2654 944	44.78	60.82	23.47	27.91	21
390881	2658 983	40.94	55.91	40.21	30.28	19
390883	2630 988	38.40	52.58	19.27	23.13	13
390937	2672 1022	38.19	51.88	43.73	41.59	30
391263	2725 1017	39.62	51.60	40.78	37.94	20
391424	2772 1075	33.04	42.92	34.27	23.66	14
391497	2822 1116	33.11	42.89	25.65	23.57	15
391605	2729 1075	38.92	47.81	45.05	32.40	21
391695	2680 1118	37.80	48.98	40.73	29.09	29
391867	2835 1200	39.62	53.28	24.43	14.41	16
391998	2773 1161	40.94	50.97	44.86	31.20	15
392106	2734 1134	40.29	50.73	52.65	37.36	13
392196	2711 1184	38.85	48.95	39.15	24.79	11
392291	2636 1110	45.53	56.99	33.55	23.42	10
392373	2606 1168	41.18	53.44	20.86	17.40	12
392465	2639 1166	44.05	55.56	42.44	28.84	10
392686	2716 1256	39.48	50.60	41.77	28.31	26
392695	2866 1265	40.25	56.16	29.95	23.11	27
392970	2739 1254	41.85	50.94	37.92	27.17	20
393059	2792 1230	41.69	52.12	33.01	23.01	22
393315	2692 1411	56.42	67.71	21.09	22.57	16
393330	2689 1410	55.79	73.88	38.28	30.59	58
393386	2682 1380	55.68	68.34	23.10	20.93	21
393432	2685 1347	52.80	67.04	24.31	21.00	23
393619	2672 1283	46.03	54.85	46.14	35.01	13
393812	2690 1190	35.36	47.03	32.43	20.02	16
393921	2639 1239	37.39	49.74	46.15	32.29	12
393986	2632 1266	36.41	47.14	38.97	30.84	24
394149	2565 1247	38.79	48.50	43.87	32.06	14
394299	2568 1298	32.36	45.99	12.61	17.75	12
394318	2648 1332	45.63	56.14	32.85	24.20	18
394351	2623 1305	38.20	50.44	35.43	26.95	18
394514	2600 1334	37.42	47.88	33.80	25.01	18
394659	2558 1330	34.32	44.12	24.44	24.83	41
394784	2609 1384	47.67	59.63	24.63	22.46	15
394855	2642 1386	52.62	66.51	28.36	24.55	18
395034	2541 1422	40.60	54.02	18.77	17.65	10
395123	2561 1348	37.19	47.63	25.03	18.57	26
395162	2494 1347	35.66	44.65	33.35	25.92	31
395219	2482 1419	46.70	57.72	34.03	23.92	15
395348	2550 1375	40.41	52.90	21.08	22.86	12
395601	2505 1453	43.28	56.96	24.56	22.44	77
395622	2520 1478	39.92	51.87	31.14	24.53	33
395952	2698 1493	40.73	56.49	20.98	22.93	13
396100	2822 1473	50.37	67.66	25.13	24.44	28
396384	2133 1442	36.43	46.48	27.28	28.19	16
397328	2960 1462	43.18	53.17	49.28	40.10	11
397445	2956 1421	54.50	68.51	46.33	36.73	16

Gauge number	Grid reference	1-day RBAR(mm)	2-day RBAR(mm)	1-day CV(%)	2-day CV(%)	No. of years
397532	2972 1460	41.11	50.28	38.22	33.01	25
397713	2973 1380	58.89	70.19	48.27	35.18	16
397758	3022 1343	58.12	74.58	37.19	28.03	18
398022	3085 1404	41.76	52.85	48.56	37.25	26
398063	3073 1374	55.05	67.72	44.46	33.69	10
398074	3055 1362	43.98	58.71	18.66	18.25	15
398081	3057 1378	48.87	63.47	41.78	31.42	18
398276	3175 1404	44.00	53.41	52.56	43.87	15
398383	3236 1453	36.26	44.40	48.63	40.39	26
398455	3489 1057	47.90	56.96	27.19	18.69	10
398505	3460 1082	44.29	55.06	27.78	30.38	19
398512	3438 1076	41.29	52.27	32.49	29.43	25
398516	3436 1087	40.96	52.24	32.35	28.27	55
398528	3448 1103	42.51	55.94	26.71	28.23	14
398631	3466 1109	44.07	56.63	23.57	27.00	16
398829	3480 1157	41.21	51.04	28.86	18.95	14
398839	3468 1159	42.09	50.57	26.78	20.16	12
398842	3468 1148	41.65	52.17	27.61	24.18	15
398892	3417 1170	45.57	56.58	26.37	19.82	11
398896	3416 1191	41.10	49.55	28.99	23.94	26
399008	3460 1190	43.24	50.72	24.05	23.04	11
399190	3332 1095	45.49	59.13	29.04	32.67	10
399307	3338 1140	42.24	55.63	38.50	29.16	13
399329	3362 1160	43.31	51.84	34.64	25.71	11
399368	3376 1182	41.60	51.72	36.20	27.16	13
399569	3299 1198	39.20	52.05	22.69	20.50	12
399748	3406 1240	38.28	47.42	35.14	26.77	24
399758	3428 1249	37.48	45.93	39.31	28.02	16
399762	3387 1250	39.24	49.11	43.74	32.87	26
399863	3668 1194	34.10	43.43	19.87	23.88	15
399984	3643 1168	37.61	45.11	32.51	24.85	14
399988	3639 1170	35.98	45.56	29.81	20.63	12
400021	3632 1154	36.80	44.44	28.85	25.01	22
400158	3595 1106	40.24	48.90	36.83	33.72	20
400174	3633 1068	44.13	53.97	25.01	31.74	12
400347	3517 1055	46.48	58.15	28.64	32.74	13
400408	3556 1116	43.92	54.29	30.98	32.14	21
400418	3576 1060	47.72	60.27	28.26	32.59	12
400595	3544 1161	42.83	49.74	32.32	22.12	10
400616	3573 1162	35.68	45.01	31.55	25.91	79
401005	3551 1237	37.23	46.01	34.92	31.87	22
401371	3427 1268	39.17	47.24	47.72	36.47	13
401444	3376 1286	37.09	46.60	39.87	32.41	25
401620	3041 1308	45.51	58.26	43.65	30.85	14
401668	3054 1273	45.25	59.82	40.95	30.88	19
402073	3065 1291	44.15	58.81	20.90	23.79	15
402190	3114 1235	40.11	51.49	47.01	36.74	26
402542	3166 1334	43.88	56.35	51.42	44.54	19
402553	3157 1325	49.26	63.08	41.81	33.92	13
402745	3213 1197	38.16	49.73	21.66	23.71	10
402769	3229 1238	37.05	47.04	45.21	38.17	76
402819	3228 1265	41.13	50.39	46.43	36.30	15

Gauge number	Grid reference		1-day RBAR(mm)	2-day RBAR(mm)	1-day CV(%)	2-day CV(%)	No. of years
402938	3244	1216	47.60	56.25	63.05	49.86	13
403058	3264	1284	44.50	54.24	71.68	54.56	10
403115	3286	1291	39.12	48.83	56.69	45.30	25
403116	3289	1291	44.80	53.08	73.13	56.98	12
403138	3333	1289	40.22	50.22	51.43	38.35	25
403143	3344	1288	39.55	48.58	48.50	36.94	24
403146	3357	1305	37.95	48.01	49.68	37.98	26
403219	3331	1330	37.79	48.14	58.30	42.78	25
403426	3300	1368	38.15	48.31	46.73	42.64	66
403451	3224	1367	42.05	52.29	60.45	46.21	20
403490	3274	1363	40.74	50.04	46.85	39.83	26
403541	3277	1378	44.07	53.07	63.63	53.12	10
403543	3283	1377	40.08	48.57	54.41	47.00	17
403664	3573	1288	34.08	45.07	38.62	28.46	12
404124	3439	1365	36.65	45.38	41.50	32.90	26
404552	3213	1362	43.20	54.37	51.76	40.39	23
404564	3236	1385	40.24	50.03	47.90	36.74	26
404580	3244	1394	39.58	49.18	48.21	36.97	25
404585	3255	1399	39.91	49.82	46.95	38.76	20
404642	3192	1396	50.28	60.39	56.33	51.33	10
404979	3486	1353	38.29	46.07	39.49	34.76	17
404988	3492	1362	34.62	42.14	43.77	36.29	113
404994	3485	1364	36.38	44.32	44.77	39.04	25
404996	3481	1373	42.46	50.37	46.96	37.00	12
405141	3434	1373	37.46	47.94	39.59	32.49	14
405279	3367	1431	36.22	44.49	37.63	31.90	24
405455	3704	1385	42.50	54.76	38.63	28.89	25
405488	3723	1344	38.47	49.89	33.92	24.07	12
405669	3638	1329	33.82	43.16	30.14	32.06	12
405817	3647	1390	35.72	46.75	36.71	30.21	15
406028	3541	1331	35.85	44.46	38.30	34.75	20
406169	3630	1433	36.31	46.71	36.86	31.15	60
406177	3623	1435	42.60	54.68	26.36	19.11	24
406353	3535	1451	38.31	47.51	43.06	29.17	20
406525	3562	1417	41.35	50.17	24.44	19.92	10
406797	3399	1448	42.04	50.16	48.42	47.93	20
407021	3349	1458	37.15	45.48	49.99	40.84	24
407154	3304	1495	35.67	44.46	43.67	39.36	52
407156	3305	1505	34.43	44.01	15.92	10.68	12
407157	3304	1506	36.50	45.69	51.37	42.27	11
407236	3528	1477	41.48	52.03	42.22	30.70	19
407349	3488	1501	45.88	55.01	51.17	40.71	22
407398	3437	1487	42.66	51.65	70.21	54.66	17
407635	3452	1534	38.70	48.64	46.60	35.92	26
407733	3415	1572	40.62	51.91	57.89	43.00	23
407865	3340	1563	36.25	47.15	39.89	31.74	17
407924	3327	1514	40.44	49.31	47.66	39.28	14
408040	3351	1588	44.83	55.48	50.58	42.49	10
408126	3318	1602	37.13	46.20	33.18	31.06	62
408346	3505	1604	44.52	54.22	52.07	40.03	26
408414	3479	1629	44.27	53.29	45.48	36.18	25
408528	3421	1658	45.81	53.58	64.27	56.27	12

Gauge number	Grid reference	1-day RBAR(mm)	2-day RBAR(mm)	1-day CV(%)	2-day CV(%)	No. of years
408549	3447 1577	45.87	57.78	55.75	41.81	20
408723	3473 1680	33.83	44.18	25.61	23.65	18
408772	3466 1670	41.96	50.89	51 39	45.31	17
409013	3489 1721	40.41	51.97	45.22	38.22	23
409085	3425 1715	34.88	46.53	28.14	27.88	67
409224	3472 1754	32.93	45.60	18.36	23.08	15
410324	3899 1887	40.00	49.22	45.68	38.15	26
410444	3786 1855	41.48	51.43	41.84	31.87	23
410524	3807 1829	40.25	50.49	37.52	36.11	24
410598	3863 1864	38.75	48.42	36.80	35.15	26
411524	3955 1804	41.40	50.46	46.84	39.74	19
411686	4006 1784	34.79	43.42	23.11	23.02	18
411950	3974 1699	39.31	49.15	32.36	27.06	26
412205	3912 1751	38.50	49.47	43.86	39.00	23
412209	3919 1727	41.13	52.29	49.45	40.37	22
412297	3921 1702	38.71	49.09	47.90	38.36	26
412386	3874 1694	36.34	49.72	28.75	29.87	17
412392	3885 1694	39.27	51.00	47.53	37.73	18
412507	3909 1647	38.35	48.01	48.93	36.61	15
412728	3858 1633	39.49	51.81	36.49	32.74	20
413479	3862 1483	38.73	48.61	31.86	26.10	26
413747	3858 1577	37.60	48.78	33.06	30.46	25
413787	3843 1562	38.32	49.19	29.69	29.86	26
413825	3845 1583	42.73	53.90	27.39	33.25	11
413886	3825 1606	45.86	58.52	30.26	37.50	10
414290	3774 1487	41.06	53.44	29.15	25.45	25
414372	3631 1494	48.56	62.76	34.13	25.19	14
414415	3657 1481	50.44	62.33	24.11	25.05	10
414743	3756 1480	38.17	49.55	32.08	28.38	55
414744	3756 1480	42.80	52.04	28.15	19.14	12
414829	3774 1514	40.59	55.67	27.83	22.61	22
415086	3647 1524	44.50	59.34	27.63	21.32	26
415125	3656 1508	43.85	58.32	25.69	23.43	24
415161	3668 1535	38.43	51.25	17.48	14.24	13
415176	3712 1527	43.44	55.59	23.71	16.83	24
415375	3594 1570	48.07	61.72	38.06	27.26	21
415583	3750 1617	43.39	55.40	38.03	32.02	23
415588	3763 1616	44.45	56.87	35.06	30.78	24
415725	3772 1744	39.24	53.49	23.77	37.03	12
416056	3794 1669	42.32	56.05	28.71	33.33	14
416081	3755 1711	42.42	54.35	50.70	42.27	24
416128	3769 1685	37.73	49.07	44.42	35.92	113
416213	3750 1668	47.91	60.36	47.04	38.74	26
416224	3754 1653	34.36	44.37	36.29	28.13	64
416242	3751 1638	43.22	54.98	43.39	36.86	24
416263	3743 1662	51.73	64.36	45.29	40.43	19
416282	3718 1676	49.53	62.19	49.01	36.81	14
416742	3667 1699	41.38	51.63	56.68	45.06	24
416743	3664 1692	35.55	45.91	21.81	29.67	10
416771	3597 1528	47.99	62.03	29.36	19.71	20
416807	3589 1554	44.05	57.02	30.43	24.74	78
416950	3597 1604	52.43	63.16	46.59	34.71	12

Gauge number	Grid reference	1-day RBAR(mm)	2-day RBAR(mm)	1-day CV(%)	2-day CV(%)	No. of years
417005	3570 1617	48.12	58.67	48.43	39.27	26
417634	3537 1679	42.17	53.05	45.66	35.99	62
417640	3535 1699	42.38	53.52	51.53	40.58	26
417899	3668 1884	40.01	53.32	32.59	28.34	26
417986	3669 1819	45.16	56.07	42.18	32.65	11
418120	3600 1805	41.79	52.80	37.90	33.34	20
418288	3645 1746	45.61	55.19	35.88	30.33	16
418317	3589 1763	44.45	56.56	46.27	40.17	24
418367	3577 1737	39.78	52.66	49.92	39.30	26
418545	3516 1732	39.19	52.21	35.48	29.36	82
419131	3623 1872	35.90	48.96	43.38	33.28	21
419364	3636 1906	35.41	48.79	21.19	17.13	15
419746	3773 1914	34.11	46.75	23.24	34.07	13
419751	3780 1870	36.41	50.47	23.93	32.44	14
419869	3743 1929	39.77	53.40	32.48	28.59	23
420216	3674 1995	34.49	48.59	29.25	29.73	14
420259	3670 2022	37.44	47.90	27.49	21.54	14
420320	3764 1988	43.00	53.60	38.47	35.64	14

Appendix 2 Cross-validation procedure for semivariogram model selection

The cross-validation procedure (Delhomme, 1978) was used to aid the identification of the optimum model parameters for each semivariogram. The method requires the definition of three statistics: average kriging error (AKE), mean squared error (MSE) and standardized mean square error (SMSE). AKE is defined as the mean difference between estimated and observed point values; for the estimator to be unbiased, the AKE must be close to zero. MSE is the mean of the squared differences between estimated and observed values. The choice of model is minimized by finding that with the minimum MSE. Finally, SMSE is the mean of the squared difference between estimated and observed values, standardized by the kriging variance at each point. For the estimation errors to be consistent with the kriging variances, SMSE should lie in the interval:

$$1 - 2\sqrt{2/n} \leq \text{SMSE} \leq 1 + 2\sqrt{2/n}$$

where n is the number of point observations. Results of the cross-validation test for each of the four basic variables are now given:

Basic variable		AKE	MSE	SMSE
1-day RBAR	590	0.0046	0.0923	0.9890
2-day RBAR	589	0.0034	0.0225	0.9639
1-day CV	590	0.0027	0.0329	1.0020
2-day CV	589	-0.0004	0.0322	1.0328