HR Wallingford

Hydrological Conditions for Design in Urbanising Areas and using Detention Storage

Report SR 302
March 1992

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31 March 1992

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This report was prepared under contract No. PECD 7/6/193, funded by the Department of the Environment, for the research into Hydrological Conditions for Design in Urbanising Areas and using Detention Storage. The work was carried out in the Research Department of HR Wallingford.

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The DoE nominated officer is Mr Peter Woodhead. This report is published on behalf of the DoE but any opinions expressed are those of the authors and not necessarily those of the Department.

ABSTRACT

Most sewerage design in the UK uses synthetic rainstorms derived from rainfall statistics. These were originally developed to represent peak flow rates at average summer conditions. They may therefore not be applicable to winter conditions, or to systems where total volume of runoff is important; the design of detention storage tanks, and predicting spill from overflows.

One alternative method of design is to use long timeseries of real rainfall records. This has the disadvantage of long computation times, and difficulties in obtaining the data. This project set out to develop a method to represent a long timeseries with just a few synthetic storms.

Annual rainfall timeseries representing a typical year's rainfall for three locations in the UK were analysed to determine the storm characteristics. The storms were classified by depth of rain, catchment wetness, peakedness and skew. This led to a new definition of peakedness which gave higher peak intensities in long durations storms. This work also gave an insight into how well the timeseries represented the rainfall patterns in a typical year.

Synthetic storms were generated using the average storm characteristics and were found to give a good representation of the timeseries. Sensitivity studies were carried out to determine how well the storms would perform in less than optimal conditions. Final testing of the synthetic storms was carried out on models of real catchments including detention tanks and overflows.

CONTENTS

FIGURES

1. INTRODUCTION

One of the longest running arguments in the use of urban drainage models concerns whether the behaviour of the system is best represented using synthetic storms derived from statistics, or using a timeseries of real storms.

The argument in favour us using storms is that they are readily available for all locations in the UK, and that they are easy to use and require only a few storms. However the normal synthetic storms represent only one set of rainfall conditions, average summer conditions, and have only been proved to be correct in predicting peak flow rates, not storage volumes. The argument in favour of timeseries is that they include a wider range of conditions, and therefore are likely to contain the conditions which are critical on each catchment.

There are two crucial areas in which synthetic storms may not adequately represent the response of a catchment. The first of these is in the design of detention storage tanks, where modest storms falling on a very wet catchment may give a larger volume of runoff than a larger storm with average catchment wetness. The second area is in predicting spill from overflows in small frequent storms for pollution impact studies. The first area is the main area of interest of this project, although the second has been covered as well.

2. ANALYSIS OF RAINFALL CHARACTERISTICS

2.1 Introduction

The first stage of this study was to investigate the variation that existed in long rainfall records of real storms to see whether this variation could be represented by a few synthetic storms. To do this a representative timeseries was required. The WRc annual Timeseries were used for this. These were chosen, because although they did not include the more extreme storms which were also of interest to this project they were a convenient source of representative rainfall data. This work is reported more fully elsewhere [HR Wallingford 1991].

2.2 The WRc Annual Timeseries

Timeseries rainfall is a sequence of historic rainfall events statistically representative of the precipitation patterns for a given location. The WRc annual timeseries are series of storm events representing typical years for each of three regions of the country. They have a duration of one year and are sequences of fine resolution rain data suitable for input to WASSP-SIM. The storms are available in three forms, a chronological series of all significant events in a typical year, the same events ranked in order of severity and a pair of similarly ranked series for summer and winter periods. Annual timeseries are available for the South East, South West and Yorkshire. Each series consist of approximately 99 storms.

In deriving the timeseries a preliminary selection of monthly rainfall totals was made. The totals were screened and any months with values within the range of the mean plus or minus one standard deviation were accepted. Approximately one third of all the monthly rainfalls were outside this range, representing very wet or vary dry months; these were rejected from the analysis. This selection of representative months is not thought to be significant; however the analysis of the full rainfall record may provide better results. The annual timeseries are currently ranked by severity; this involved using the timeseries rainfall for simulation in a number of models in order that the largest discharge volumes could be identified. This project attempts to rank the series by comparison with statistical rainfall data.

2.3 Analysis of the annual timeseries

The storms in the annual timeseries were analysed for four parameters: storm depth, catchment wetness (UCWI), and two parameters describing the storm shape, peakedness and skew. For each storm these parameters were compared to the standard values used for synthetic storms for the locations from which the timeseries data was derived.

The data assumed for the timeseries locations is:

	South East	South West	Yorkshire
Average annual rainfall mm	603	965	590
M5_60 mm	20	18	19
r	0.40	0.325	0.40
Standard UCWI winter mm	126	142	122
Standard UCWI summer mm	62	102	51
Location Index	1	1	1

2.3.1 Storm Depth

Each storm in the series was analyzed to find the maximum depth in each of a series of durations. The durations used where: 15, 30, 60, 120, 240, 480, 960, 1920 minutes. The depth ratio was defined as the maximum depth divided by the depth in a storm of one year return period of the same duration. The critical duration was defined as the duration with the largest depth ratio.

The depth ratios were then ranked in ascending order for each duration, and the rank converted to a return period, 1/(number of storms - rank) and a graph of depth ratio against return period was plotted (Fig 1a - 1f).

The results for each duration are similar, although for all of the regions the long storms with durations of 240 minutes and above show a decrease of depth ratio with increasing duration. This is particularly noticeable for the South West region if the outlier storms at 12 and 120 minutes duration are ignored. This indicates that long duration storms are under-represented in the timeseries. For durations up to 240 minutes the depth ratio is independent of duration.

The variation of depth ratio with return period for the South East and Yorkshire regions are similar in that the depth ratio steadily increases up to a return period of about 0.5 then rises more slowly. The graph for the South West region rises much more rapidly to a value of 0.8 then more slowly to a maximum of approximately 1 (Fig 1e). The difference in these graphs is indicative of two distinct rainfall patterns. South East and Yorkshire regions representing the rainfall patterns in Eastern England and the South West representing Western England.

The curves of depth ratio were redrawn so as to give a smooth curve which passed through a depth ratio of 1.0 at a return period of 1 year. (This is required by the definition of depth ratio.) The average of the values for durations of 60 minutes to 240 minutes are tabulated below.

Return Period yrs	South East	South West	Yorkshire
1:1	1.000	1.000	1.000
2:1	0.813	0.775	0.855
4.1	0.635	0.660	0.710
8:1	0.403	0.563	0.488
16:1	0.300	0.416	0.302
32:1	0.196	0.293	0.186
64.1	0.105	0.177	0.110

2.3.2 Catchment wetness

Catchment wetness is defined in the Wallingford Procedure by the Urban Catchment Wetness Index (UCWI). Standard values of UCWI are given for all locations in the UK for summer and winter conditions. Summer is taken as April to September and winter as October to March. These standard values were derived by taking the average of the values calculated for the last day of each month in the season over a period of many years.

An UCWI ratio was calculated for each storm as the UCWI for the storm divided by the standard UCWI for the appropriate season. (Note the original timeseries was derived for version 6 of WASSP which does not allow UCWI values greater than 170. The latest version of the timeseries which has corrected values was therefore used.)

No correlation was found between UCWI ratio and return period.

The results are surprising. There is a very large spread of values but most results are above the standard values. The results are shown in Figures 4A, 4B, 4C and the mean and standard deviation are tabulated below.

	South East	South West	Yorkshi
Mean	1.162	1.218	1.579
Standard Deviation	0.452	0.332	0.637

If summer and winter storms are considered separately (Figs 4D-4F) a different pattern emerges. In winter there is a smaller spread of values, and the average is close to the standard value. This is likely to be because in winter catchments may remain consistently wet. In summer there is a large spread of values including some very much higher than the standard. The result has been noted previously by other researchers using other rainfall series. As the standard summer UCWI is the basis of most urban drainage design, and these higher values will increase the amount of runoff from a storm, this is of great concern. A hypothesis for this variation can be put forward. The pattern of rainfall in summer is generally to have of dry weather followed by a series of summer storms. There is therefore a greater chance that a storm has been recently preceded by another storm than if the storms were uniformly distributed throughout the summer. The average UCWI within these periods of rainy weather will be greater than the overall summer average which is given by averaging the last day of each month.

This phenomena is worthy of further investigation, but these results show that the higher, winter, standard values of UCWI are in fact appropriate for both summer and winter.

2.3.3 Peakedness

The rainfall analysis in the flood studies report did not explicitly investigate the variation of peakedness with durations greater than 1 hour. The first analysis of the timeseries also looked at peakedness independent of duration. Peakedness was originally defined as:

$$C1/C2$$

where C2 depth of rain in the critical duration of the storm

C1 maximum depth of rain in half the critical duration of the storm.

This showed similar values of peakedness to synthetic storms generated ;using the Flood Studies Reports standard 50 percentile summer or 75 percentile winter profiles. The standard storms do not give a constant value of peakedness using this definition, but have values varying by about 20 percent.

No correlation was found between peakedness and return period of storm.

A better definition of peakedness was then used, which allowed for the variation of peadkedness with duration. This was defined as:

r1/r2

where r1 the maximum depth in a given duration in the storm

r2 the maximum depth in half that duration in the storm.

The results from this analysis are tabulated below. They show that peakedness increases with storm duration.

Average Peakedness

Duration minutes	South East	South West	Yorkshire
30	0.693	0.677	0.669
60	0.752	0.709	0.718
120	0.815	0.757	0.778
240	0.904	0.823	0.842
480	0.988	0.985	1.000
960	0.997	1.000	1.000
1920	1.000	1.000	1.000

Using this definition of peakedness there are physical limits that the value must lie between 0.5 and 1.0. However there is another way in which the peakedness at long durations can be calculated. This is by using the ratio of five year return period 60 minute and 2 day storms which are mapped for the whole of the UK.

The 2 day depth was assumed to represent the depth in 48 hours. (There is in practice a small difference between the two but this was ignored.)

The peakedness factor must be applied for each doubling of the duration. From one hour to 48 hours there are **n** doublings where:

$$48 = 2^n$$

$$n = 5.58$$

Therefore assuming an average peakedness P:

$$P^{5.58} = r$$

where r = M5_60 / M5-2DAY

M5_60	1 hour depth at 5 year return period
M5_2DAY	2 day depth at 5 ;year return period

	South East	South West	Yorkshire
r	0.400	0.325	0.400
P	0.848	0.817	0.848

These value were taken as maximum limits for the peakedness at durations of four hours and above. For durations less than 1 hour the peadkedness was taken as the minimum observed value of 0.67. A linear variation was used between one hour and for hours.

The resulting storm profile was compared with the standard 50% summer profiles which are generally used for urban drainage design. At short durations, less than one hour, the new profile has much lower peaks than the 50% summer storm. However as the duration increases the new profile shows almost no decrease in peak intensity, whereas the 50% summer profile shows a rapid reduction in peak intensity. At long durations, greater than 4 hours, the new profile therefore has a higher peak intensity.

2.3.4 Skew

Skew is a measure of the position of the peak rainfall intensity within the storm. Skew was expected to have a significant effect on the response of the system to rainfall. The usual synthetic storms are symmetrical (ie central skew).

Several different definitions of skew were tried, but the following was adopted as being the most useful.

The critical duration (D) of the storm and the start and end of this duration were identified. This period was then taken as representing the storm, and rainfall before and after this was ignored. The time for half of the rainfall depth within this duration (T50) was then calculated. Skew is defined as:

$$Skew = T50 / D$$

A skew of 0 would represent a storm with most of the rainfall at the start of the storm, a skew of 0.5 would have most of the rainfall in the centre of the strom, and a skew of 1 would have most of the rainfall at the end of the storm.

The results (Fig 3a - 3c) show that there is a variation of skew, with most storms having fairly cental skew. The average values of skew are: 0.5 in the South East, slightly above 0.5 in the South West and 0.6 in Yorkshire. To investigate the relationship between skew and storm size the skews of the twenty largest storms for each series were plotted (Fig 3d - 3f). The results are similar.

From this analysis it is reasonable to use storms with a central skew, but the significance of skew was investigate further in the sensitivity testing carried out in the next phase of the project.

3. SYNTHETIC RAINFALL SERIES

3.1 Choice of storms for synthetic rainfall series

The storms for the synthetic rainfall series were chosen to have the average characteristics of the timeseries storms. Separate characteristics were used for each region. In summary these characteristics were:

The depth of rain was calculated using the depth ratios given in section 2.

The catchment wetness was taken as the standard winter value.

The peakedness was varied with duration.

The skew was central.

Sensitivity testing of these storms and initial comparisons of the synthetic storms and the timeseries were carried out using a simple storage simulation program. This work is reported more fully elsewhere [Rainey & Osborne 1991].

3.2 Storage Program

A simple storage simulation program was developed. This represented a catchment as a lumped hydrologic runoff model, and the sewerage system as a single storage tank with a limit on the continuation flow. The results of the model showed the maximum volume of water stored in the tank during a storm.

The hydrologic model uses the runoff model from the WALLRUS program where the ;runoff is defined by the proportion of the area which is covered by impermeable surfaces, a soil index and the catchment wetness (UCWI).

The storage tank is of infinite size and has an outflow limit on the continuation flow. Any flow above this limit will be stored until such time that the inflow drops below the outflow limit. Any stored water can then flow from storage to bring the total outflow up to the limit. The outflow limits can be varied to represent different catchment characteristics. The storage model was validated by comparison with a simple WALLRUS model.

3.3 Sensitivity testing of skew

From our analysis of the timeseries, no real tendency for skew was found. However the effect of skew was investigated using the storage model and checked using a 2 pipe test system on WALLRUS. Various catchment characteristics were used in the model. A critical skew of 0.52 was most common with little variance. The effect of this small skew compared to a central skew of 0.5 was negligible. Even using larger skew values of 0.6 and 0.7 a maximum increase in storage of 10% was found.

3.4 Sensitivity testing of storm duration

The critical duration of storm will carry with catchment characteristics, in particular the catchment size and the amount of attenuation storage in the catchment. The critical duration may also vary with the storm size. The sensitivity of the calculated storage volumes to the using durations other than the critical duration was therefore investigated.

Synthetic storms of frequency of 2:1 year and durations of 1, 2, 4 8 and 16 hours were simulated using the storage program to find the critical duration for a set of catchment characteristics. Storm durations in excess of 16 hours were not normally considered, as for most systems the critical duration was found to be less than this. The storm duration with the largest storage volume was then taken as the critical duration. Using the critical duration the storage volume for a series of storms of return periods of 1:8 years to 64:1 year were calculated. The variation of critical duration with return period was investigated by simulating the full set of return periods (1:8 years to 64:1 year) for durations of 1 hour to 16 hours.

The critical durations were found to vary with return period. However, the error introduced by choosing the critical duration from the 2:1 year storm was less than 10%. This procedure will therefore normally be satisfactory.

3.5 Comparison with the annual timeseries

The effect of the synthetic rainfall series was compared with that of the annual timeseries using the storage program. The synthetic series was using 10 storms to represent the complete range of return periods, whereas the timeseries uses 99. The comparisons were done for each of the three timeseries.

Three different sets of catchment characteristics were used. These had pervious areas of 60%, 30% and 70%. Some tests were done with a range of soil indices, but most test used a value of 0.4. For each set of catchment characteristics two different outflow limits were used. These represented catchments with small amounts of attenuation storage, and with very large amounts of attenuation storage.

For the synthetic rainfall series the critical duration was first identified, and then storms of 1:8, 1:4, 1:2, 1:1, 2:1, 4:1, 8:1, 16:1, 32:1 and 64:1 year were analysed. All 99 storms of the appropriate timeseries were analysed. The two sets of storage volume results were plotted together for comparison.

The comparisons are generally good (Figs 5-13). The South East synthetic rainfall series consistently indicate a slight under-prediction of storage compared to the timeseries. The Yorkshire synthetic rainfall series gives a good comparison for all of the catchments at the low outflow limit with some over-prediction on the more pervious catchments at high outflow limits.

The South West synthetic rainfall series did not perform as well with a 10-20% under-prediction of storage at low outflow limits and a slight over-prediction at high outflow limits.

These results showed that the accuracy of the synthetic rainfall series was generally insensitive to catchment characteristics.

4. TESTING ON REAL SYSTEMS

4.1 Choice of models

The final stage of this study was to test the synthetic series against the annual timeseries using WALLRUS models of real catchments.

The Water Service Companies supplied a number of models. Two suitably representative models were selected as there was insufficient time to test the synthetic rainfall series on all the models. However the testing of synthetic rainfall series using the storage model had indicated that the results were not very sensitive to catchment characteristics.

The models were selected to have typical values of the following parameters: size, pervious area, %paved, %roof and soil index. The details of the models are given below, and the details of the storage tanks and overflows are given in Figures 14 and 15.

	Model 1	Model 2
Permeable area	454.6	21.9
Paved area	47.0	6.9
Roof area	0.0	6.1
Soil index	0.30	0.45
Pipes	85	109
Tanks	1	2
Volumes	330	0.3
		0.3
Location	SE	Yorks
Critical duration	16	16

A timeseries appropriate to the region of the catchment was then selected. A synthetic series of storms of return period return period 1:8, 1:4, 1:2, 1:1, 2:1, 4:1, 8:1, 16:1, 32:1. 64:1 year was generated using the standard data for the timeseries location. Although durations of 1, 2, 4, 8 and 16 hours were simulated, the results presented here are all for durations of 16 hours as the error in making this simplification was found to be small. The synthetic series was compared with the annual timeseries by simulation using the WALLRUS program. The results of storage and overflow, against return period for the synthetic series and the annual timeseries were compared.

4.2 Results

4.2.1 Model 1

The graph of storage against return period (Fig 16) shows significant storage for the return periods considered. A good comparison between the synthetic rainfall series and the annual timeseries is obtained for storms which occurred less frequently than 6:1 year. For storms which occurred more frequently than 6:1 year the synthetic rainfall series under predicted the storage by up to 20%. The effect of storm duration on this was tested, and a storm of 32 hours duration and return period 32:1 year provided a storage value of 183.6m^2 which reduced the error at this return period by 5-6%.

The overflow from the storage tank spilled in many of the storms and the comparison of spill volume is shown in Figure 17. The predictions of the annual timeseries and the synthetic rainfall series are similar.

4.2.2 Model 2

The overflow at tank 1 did not operate in any of the storms which were used.

The graph of overflow spill against return period for tank 2 is given in Figure 18. Good agreement is shown between the annual timeseries and the synthetic rainfall series.

4.3 Effect of sampling the annual timeseries

The annual timeseries contains 99 storms and it is therefore not usual to analyse all of these because of the long computing times which this would entail. Instead a sample of the storms is analysed, and the results for the whole series extrapolated from this. The most usual sampling is to use the first five large storms, and then every fifth storm for the rest of the series. The effect of this on the predictions for the two models was checked. In both cases the synthetic rainfall series was a better representation of the full timeseries than the sample. It should be remembered that the sampled timeseries still consists of 23 storms compared to 10 for the synthetic series.

5. CONCLUSIONS

The annual timeseries does not contain enough long duration storms to correctly represent the true rainfall pattern.

The variation of storm depth with return period for return periods less than one year appears to be independent of storm duration, but does vary regionally.

The published average summer values of UCWI appear to be too low, as many summer storms have much higher values.

If storm peakedness is defined to vary with duration then it gives much higher intensities for long duration storms, although lower peak intensities for short duration storms.

For models using the constant runoff coefficient model of the Wallingford Procedure, the skew of the storm profile has little effect on storage volume or overflow spill, and central skew can be used.

Design of detention storage in urban drainage systems should use the standard winter value of UCWI and the new storm profile with peakedness varying with duration. A range of durations including very long durations should be analysed.

To predict overflow spill, the use of the synthetic rainfall series, using the new storm characteristics, gives results as good as the annual timeseries and usually better than the sampled timeseries, and uses fewer storms than either of these.

6. FUTURE WORK

The work carried out in this study has made several important advances, but has raised more questions than it has answered. Some of these should be the subject of future research work.

The work has indicated that the annual timeseries is not a good representation of rainfall patterns. The derivation of the synthetic rainfall series should therefore be repeated using longer rainfall records which will be more representative.

The proposed changes to UCWI and storm profile should apply to the design of pipe systems as well as detention storage. As pipe systems are normally designed for short duration storms the two changes are likely to cancel out. However the effect should be tested.

The analysis carried out here has not looked at all of the differences between summer and winter conditions. As many types of studies, for example overflow spill, require separate consideration of summer and winter conditions, future analyses should be done separately for the two seasons.

A modified runoff model is being introduced for the Wallingford Procedure which uses a different measure of catchment wetness. The analysis should be updated to provide results for this model. This model will change the catchment wetness and runoff during a storm. This may therefore make skewed storms more significant.

The use of the synthetic rainfall series should be analysed for water quality modelling. It is again likely that storm skew will be more significant for this application.

The analysis has shown significant regional variations in rainfall characteristics, and future work should look at more regions.

The definitions of skew and peakedness are still clumsy and consideration should be given to developing better definitions.

7. ACKNOWLEDGEMENTS

The authors are grateful to WRc for providing the timeseries rainfall on which the synthetic rainfall series have been based. To Thames Water Utilities, Yorkshire Water, Norfolk District Council and Hertsmere Drainage for supplying real models which were used for testing.

8. REFERENCES

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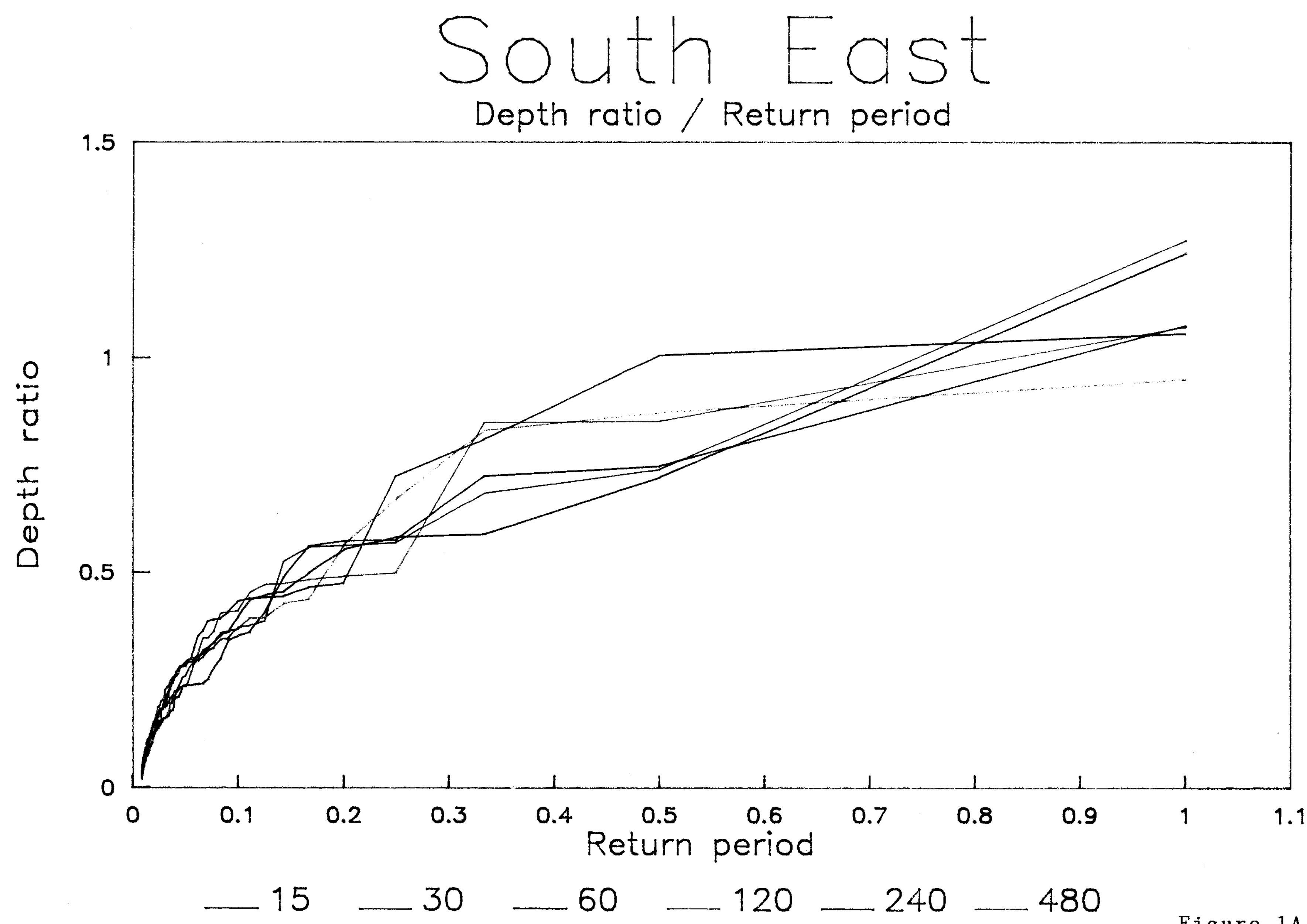
Figures


South East
Depth ratio / Return period
1.5
1
0.5
0
Depth ratio
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
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1.1
Return period
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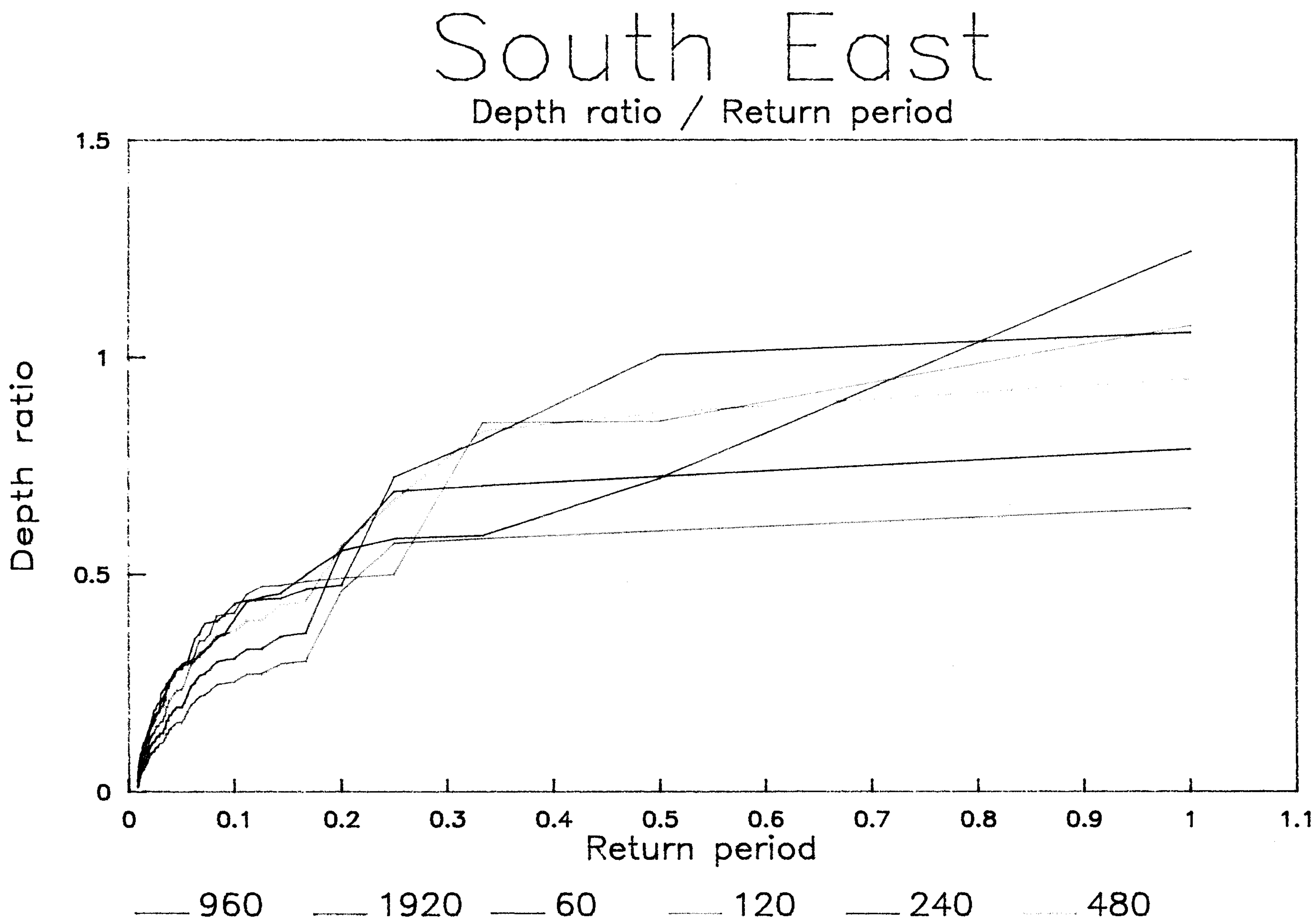
60
120
240
480

Figure 1A



South East
Depth ratio / Return period
Depth ratio
1.5
1
0.5
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0.1
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0.3
0.4
0.5
0.6
0.7
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1
1.1
Return period
960
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240
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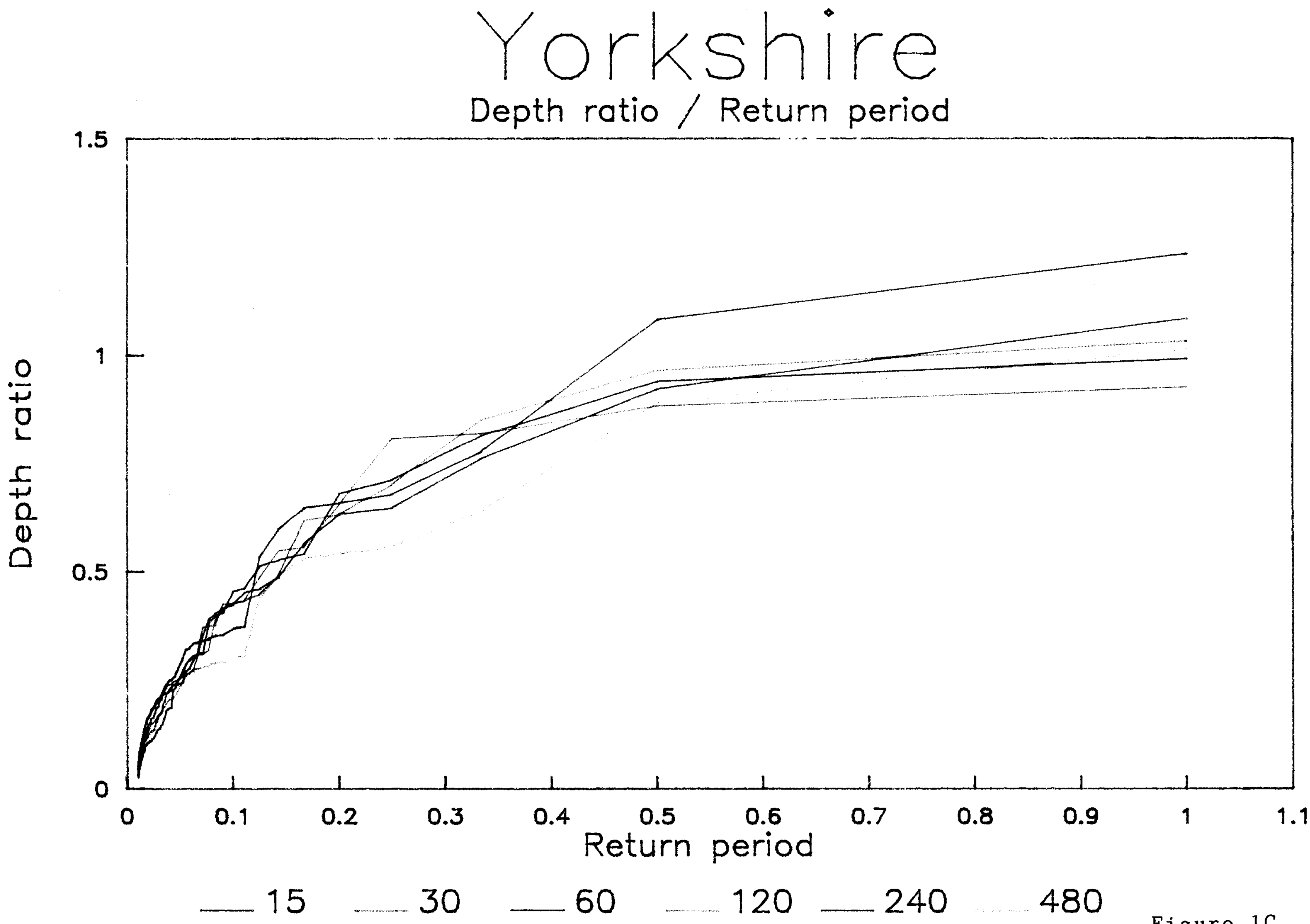
Figure 1B


Yorkshire
Depth ratio / Return period
1.5
1
0.5
0
Depth ratio
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
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1
1.1
Return period
15
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120
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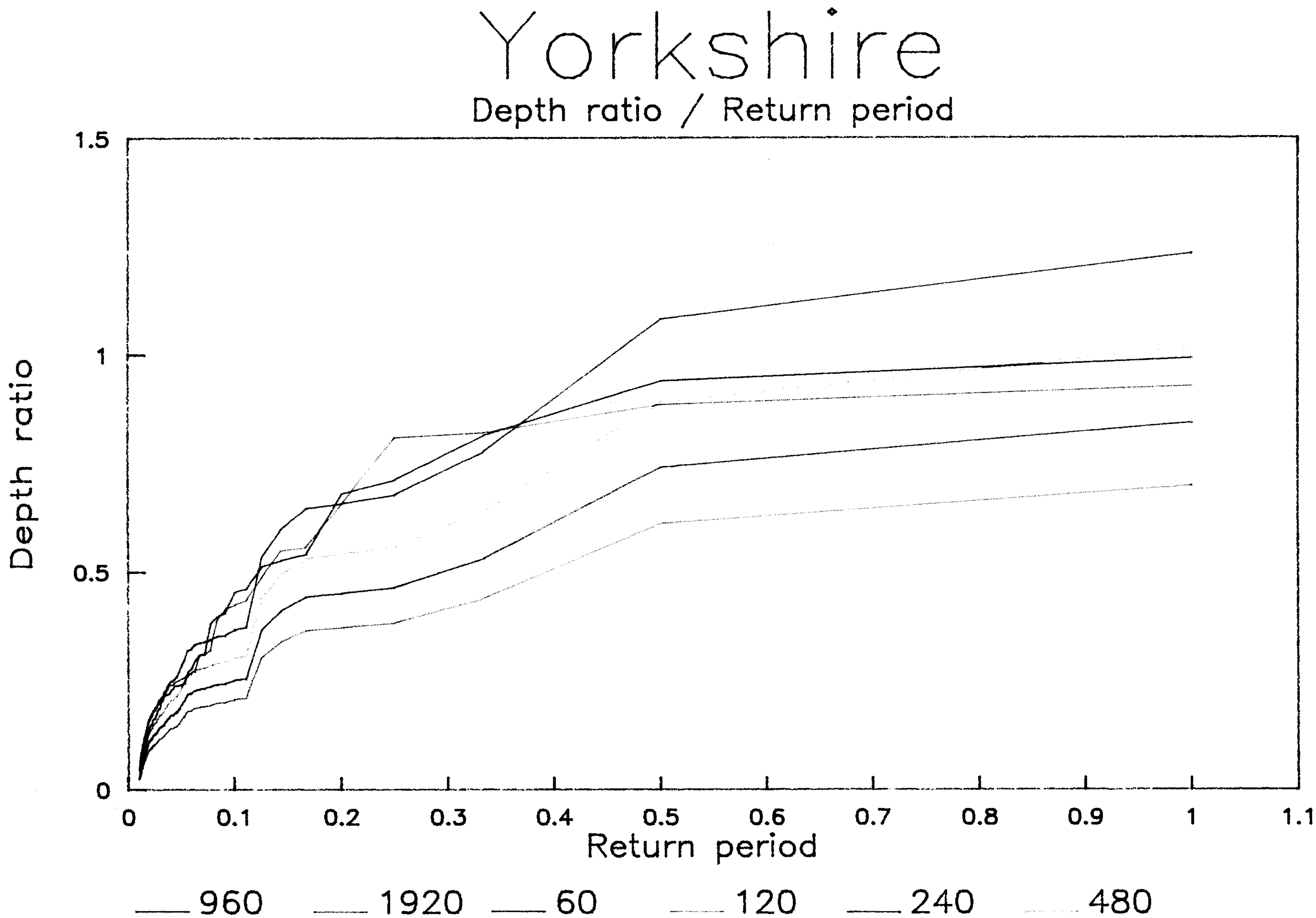
Figure 1C



Yorkshire
Depth ratio / Return period
Depth ratio
1.5
1
0.5
0
0
0.1
0.2
0.3
0.4
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0.7
0.8
0.9
1
1.1
Return period
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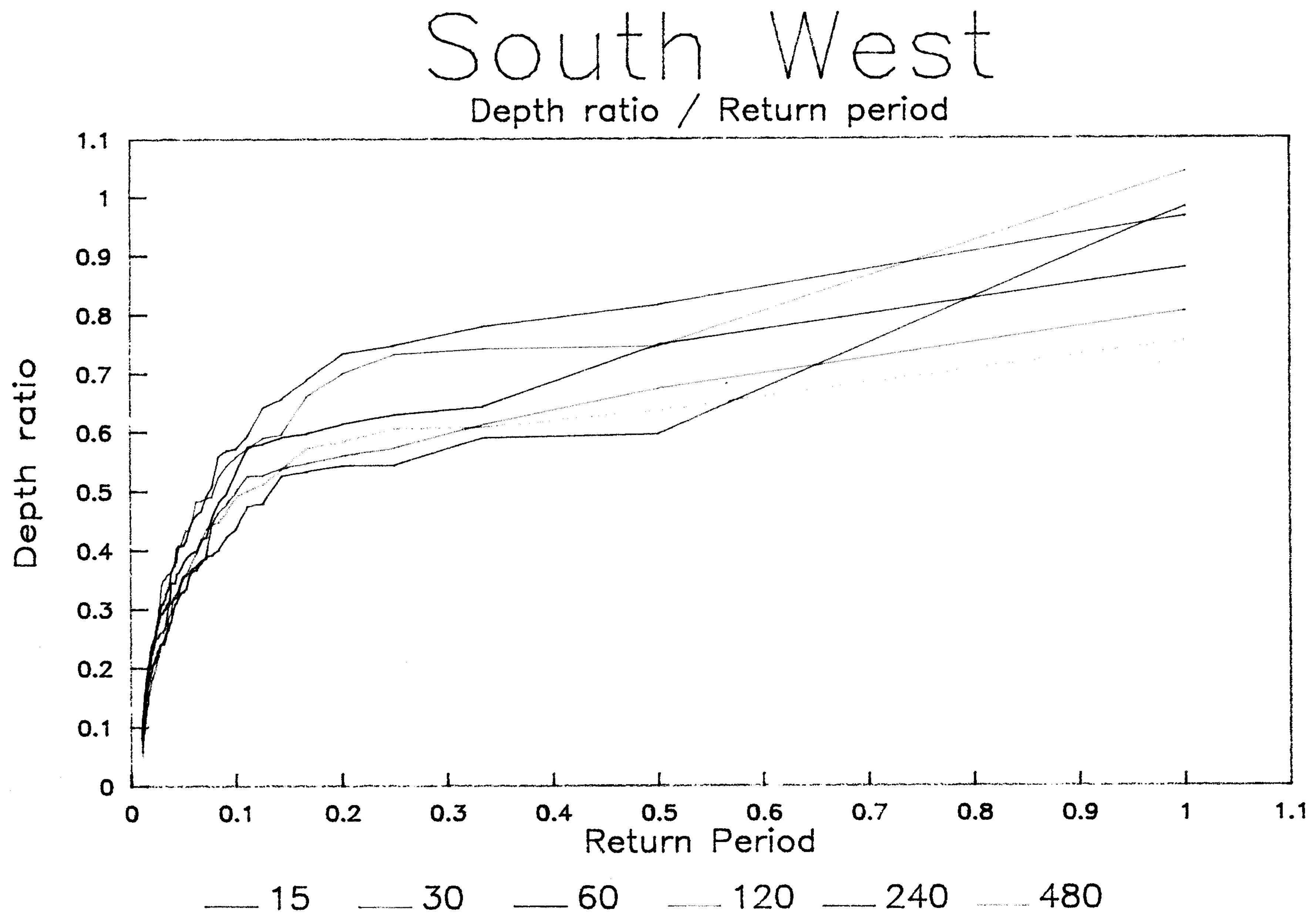
Figure 1D


South West
Depth ratio / Return period
Depth ratio
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
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0.9
1
1.1
Return Period
15
30
60
120
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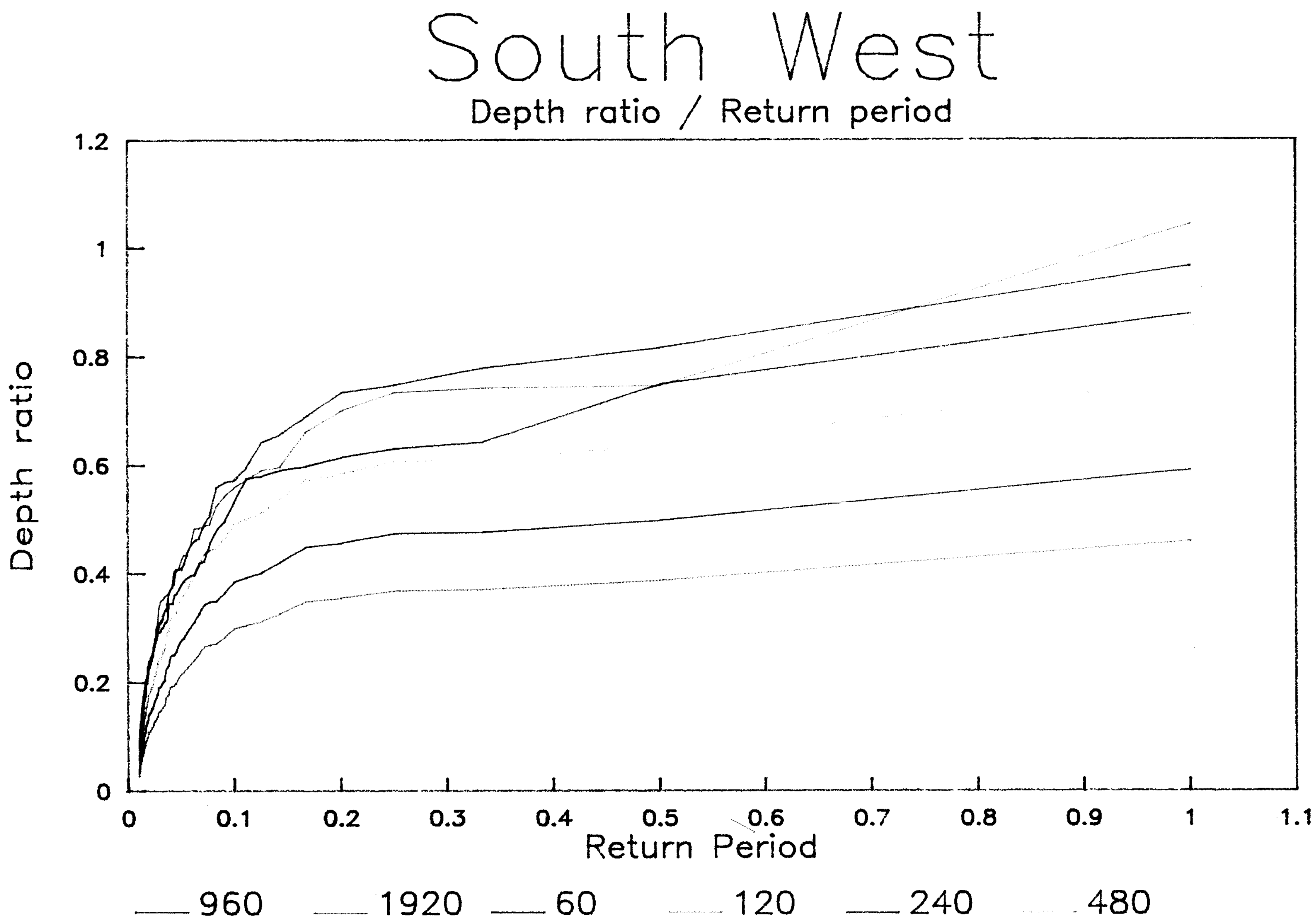
Figure 1E


South West
Depth ratio / Return period
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0.6
0.4
0.2
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0.1
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Figure 1F

Skew Distribution

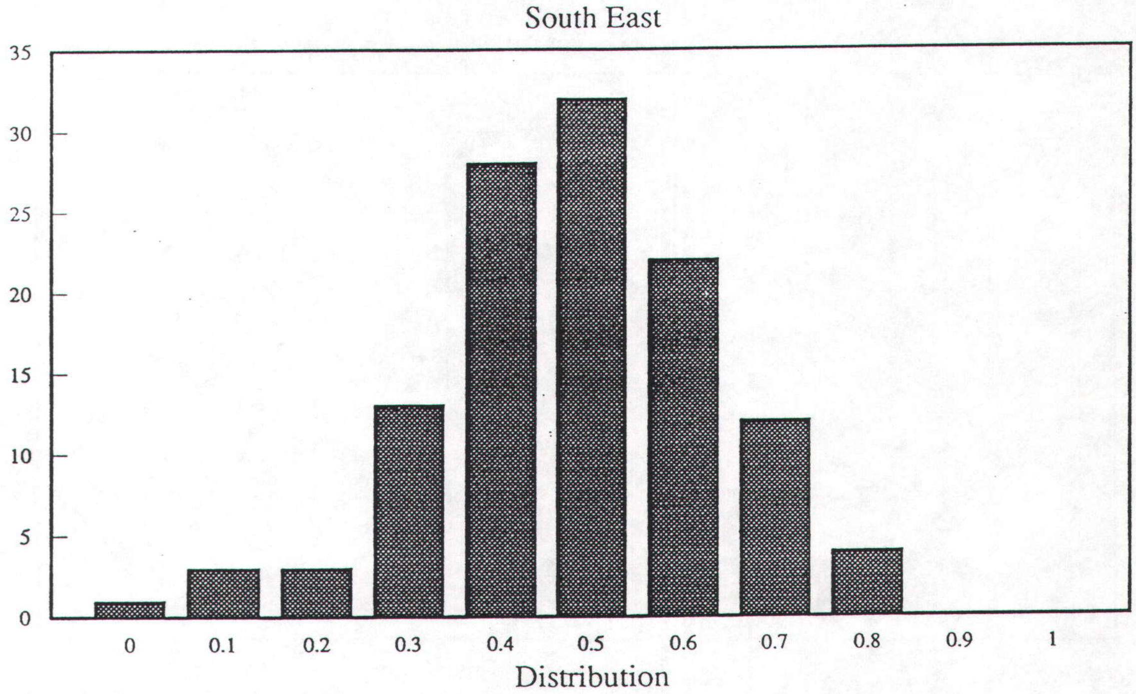


Figure 3A

Skew Distirbution, Top 20 storms

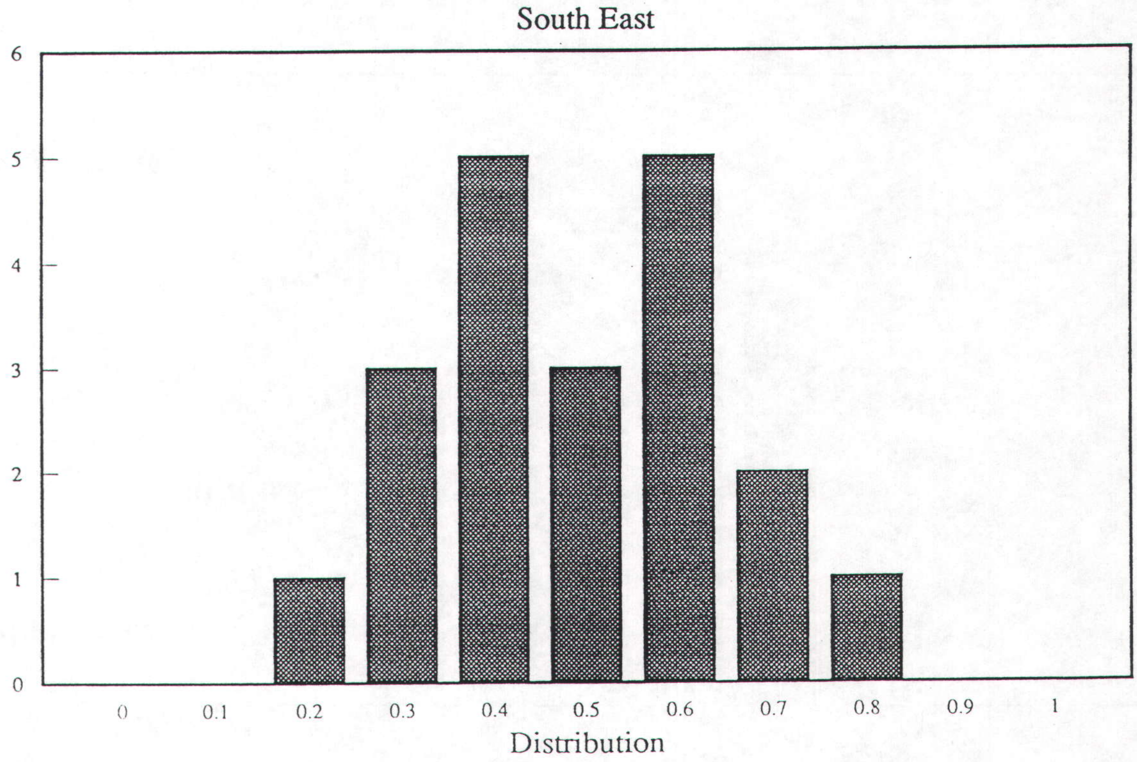


Figure 3B

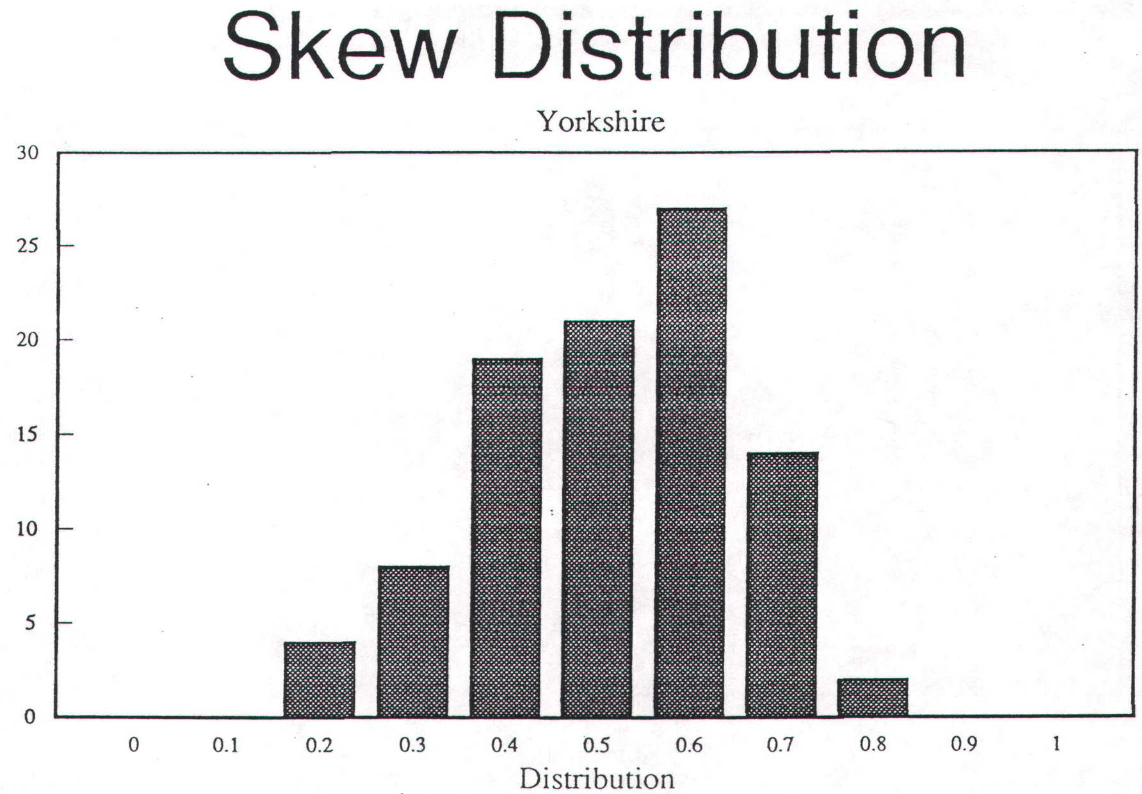


Figure 3C

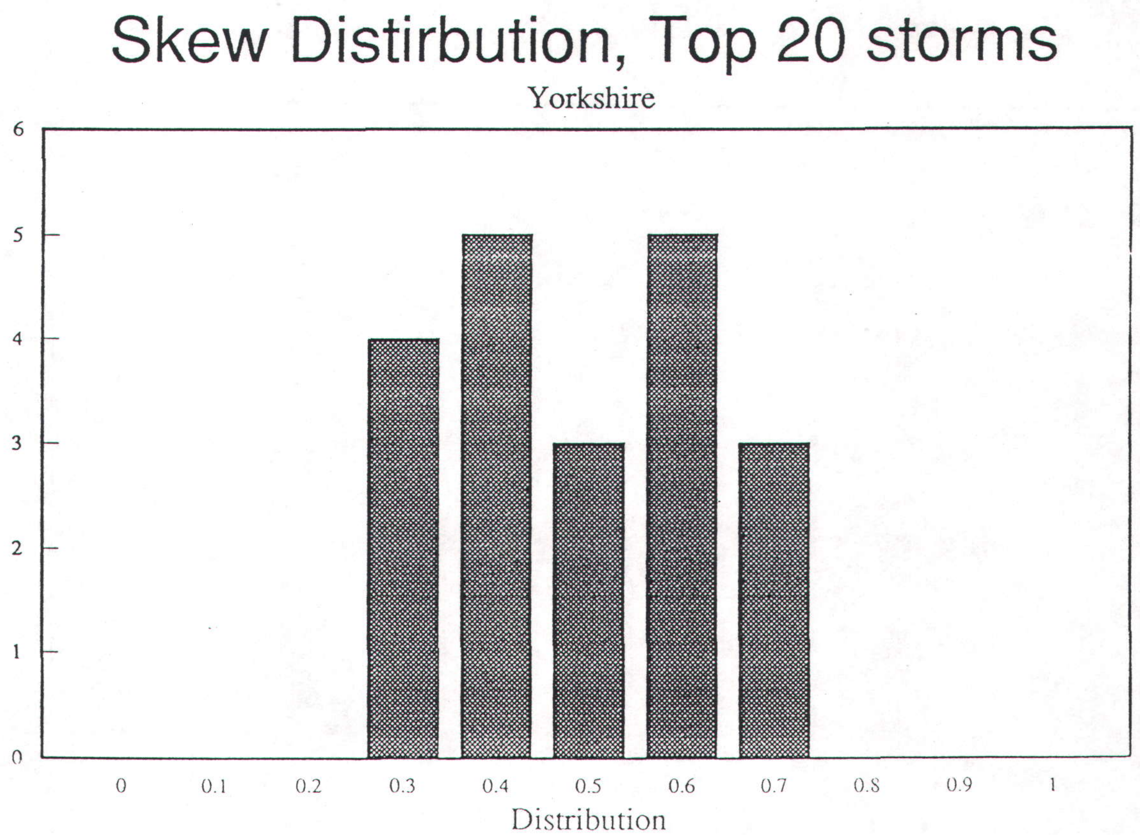


Figure 3D

Skew Distribution

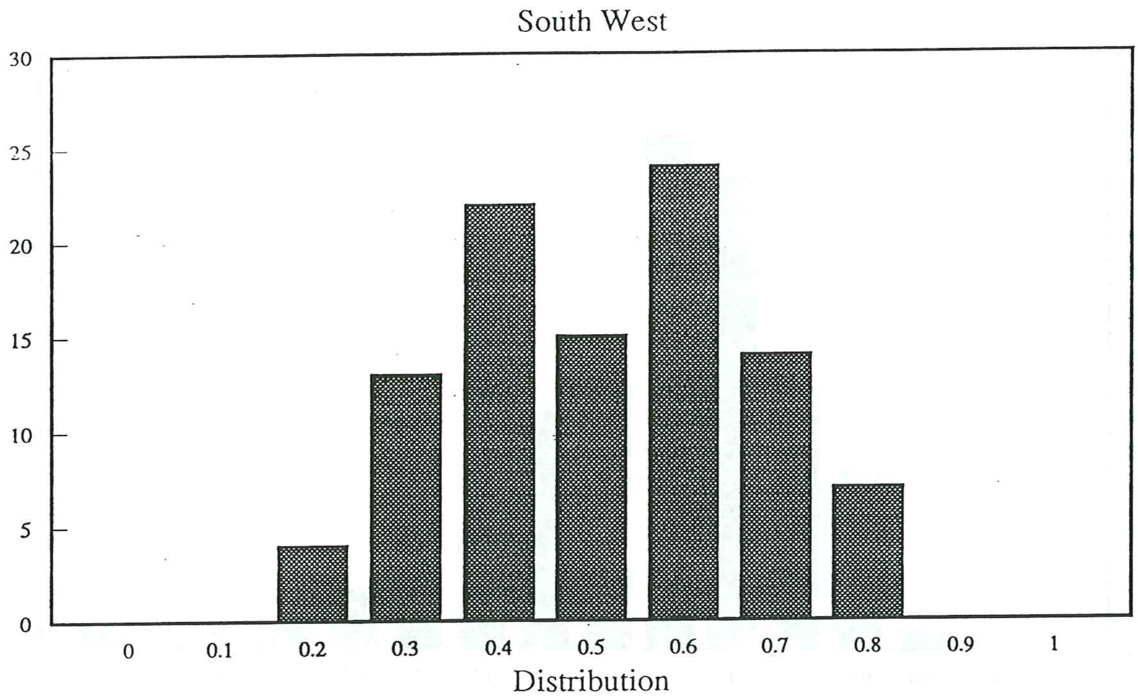


Figure 3E

Skew Distirbution, Top 20 storms

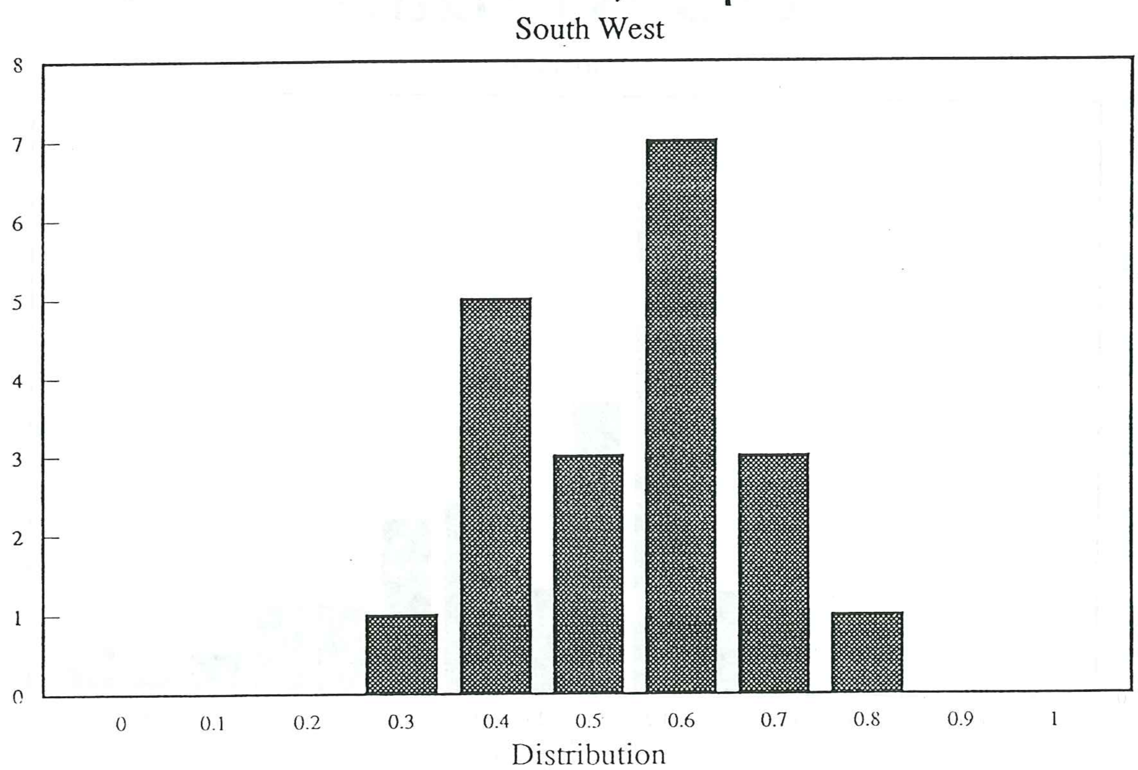


Figure 3F

UCWI ratio

South East

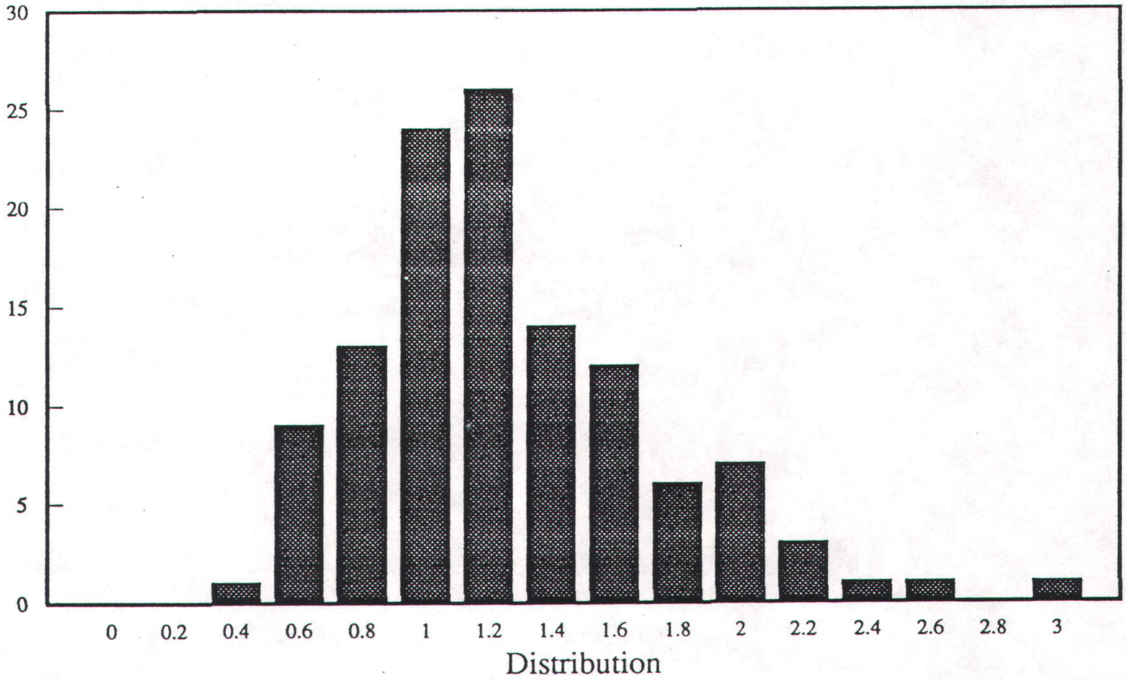


Figure 4A

UCWI ratio

Yorkshire

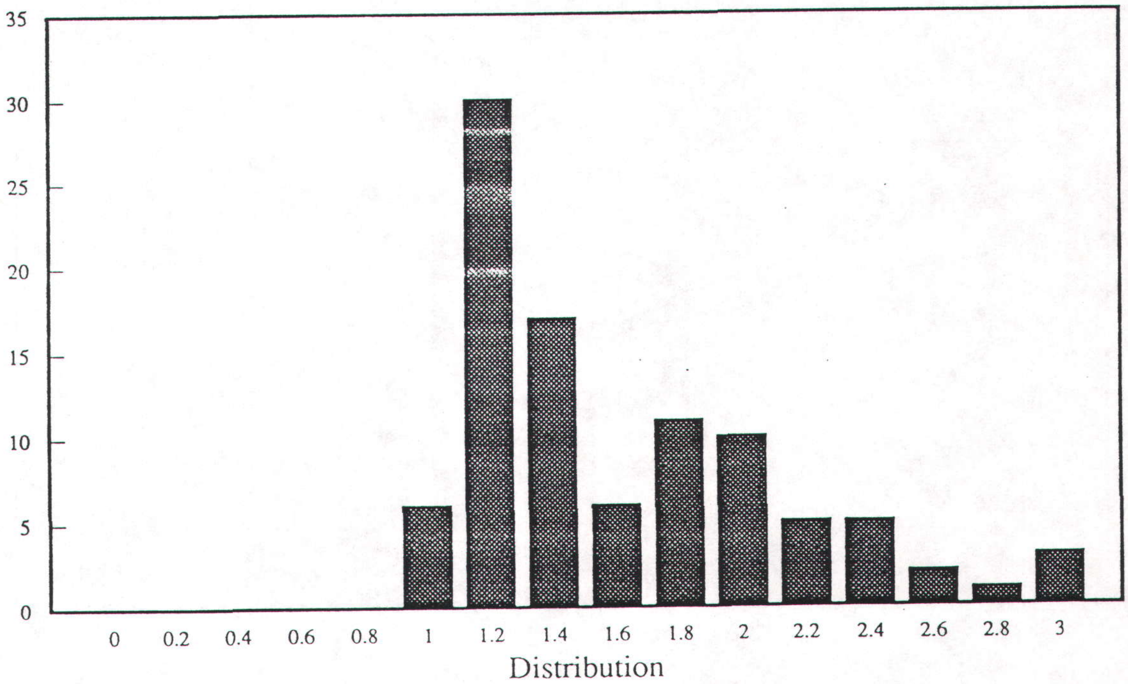


Figure 4B

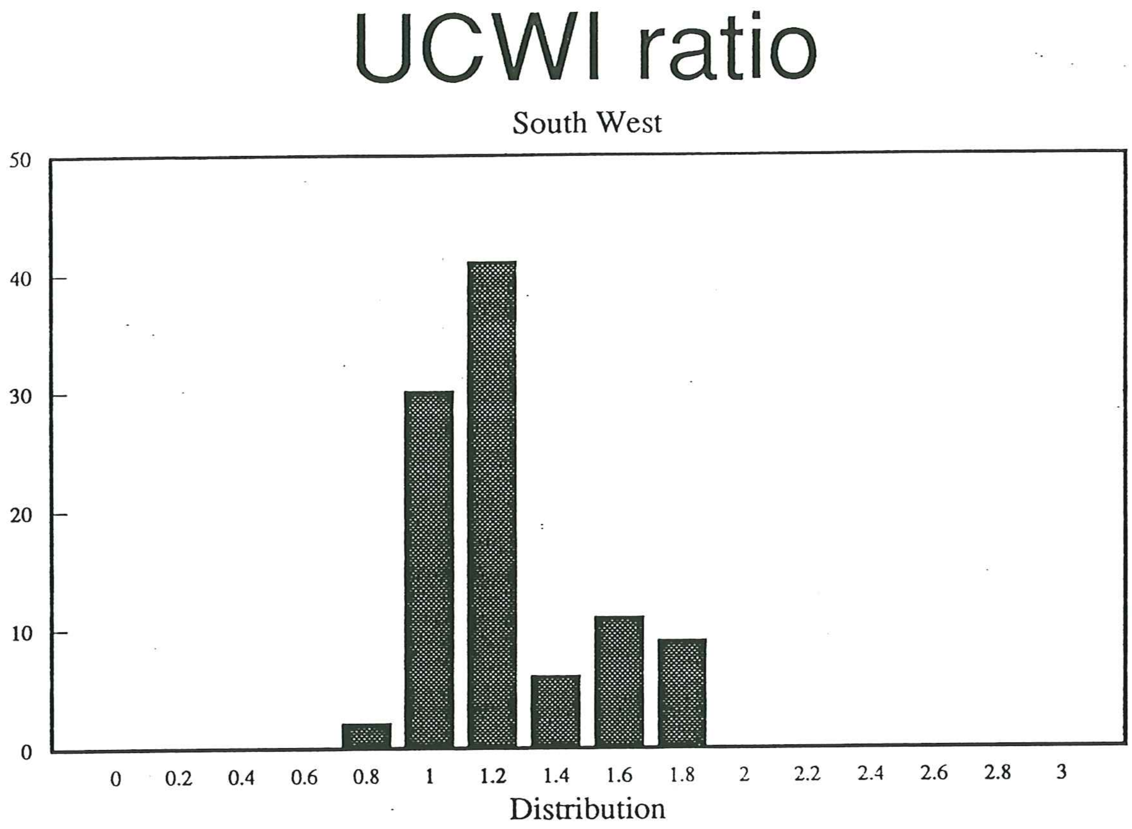

UCWI ratio
South West
50
40
30
20
10
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
Distribution

Figure 4C

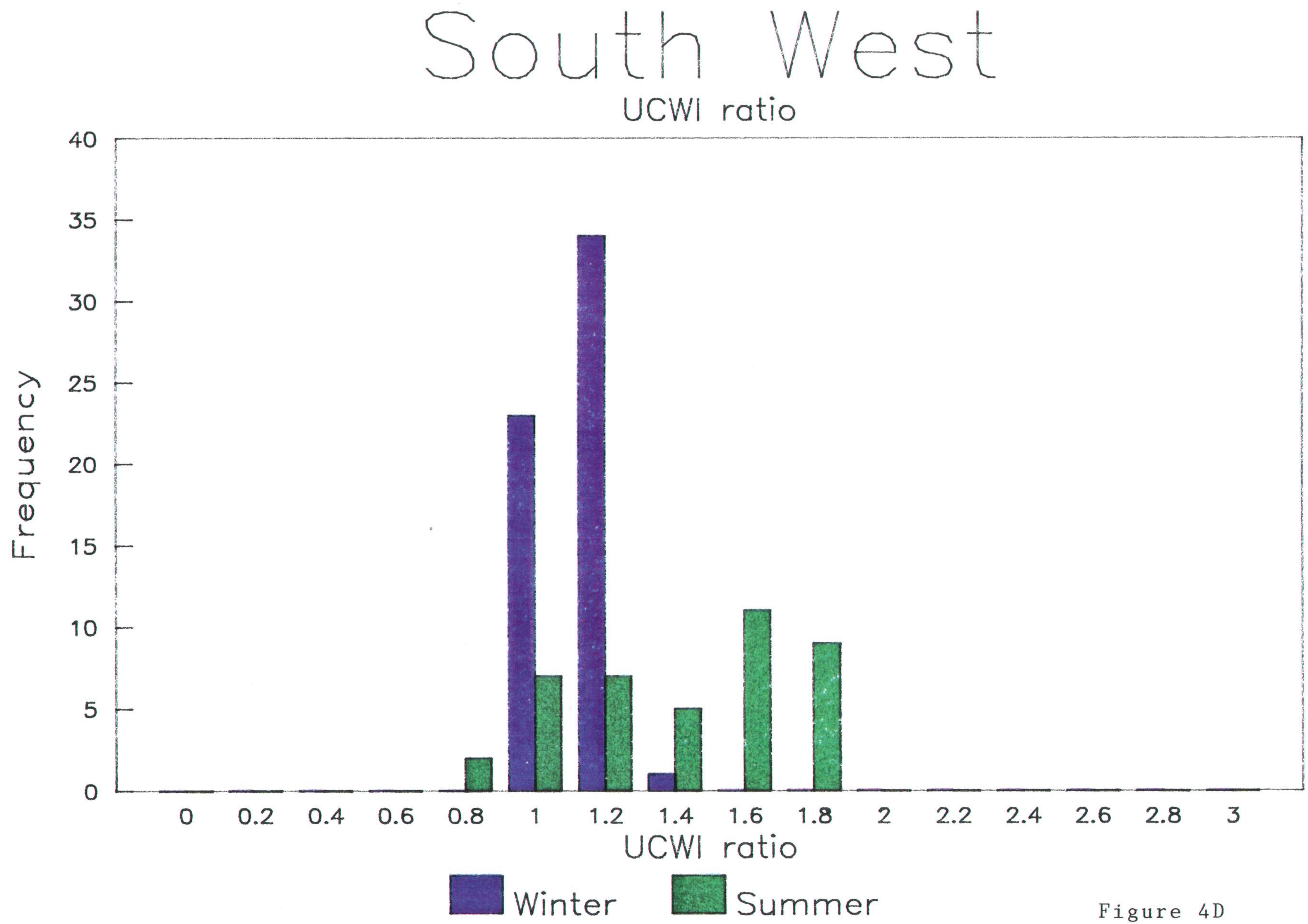
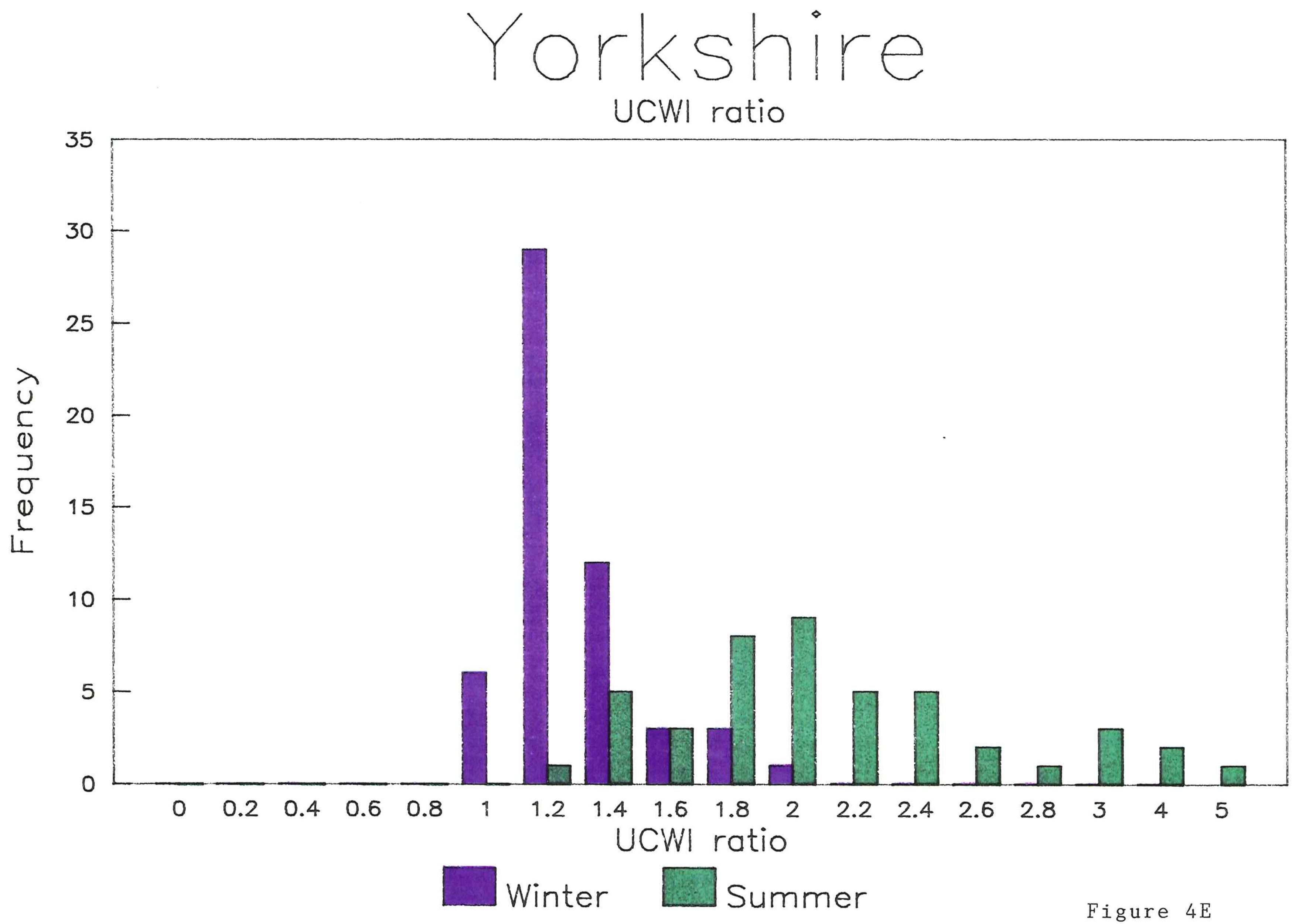

South West
UCWI ratio
Frequency
40
35
30
25
20
15
10
5
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
UCWI ratio
Winter
Summer

Figure 4D



Yorkshire
UCWI ratio
Frequency
35
30
25
20
15
10
5
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
4
5
UCWI ratio
Winter
Summer

Figure 4E

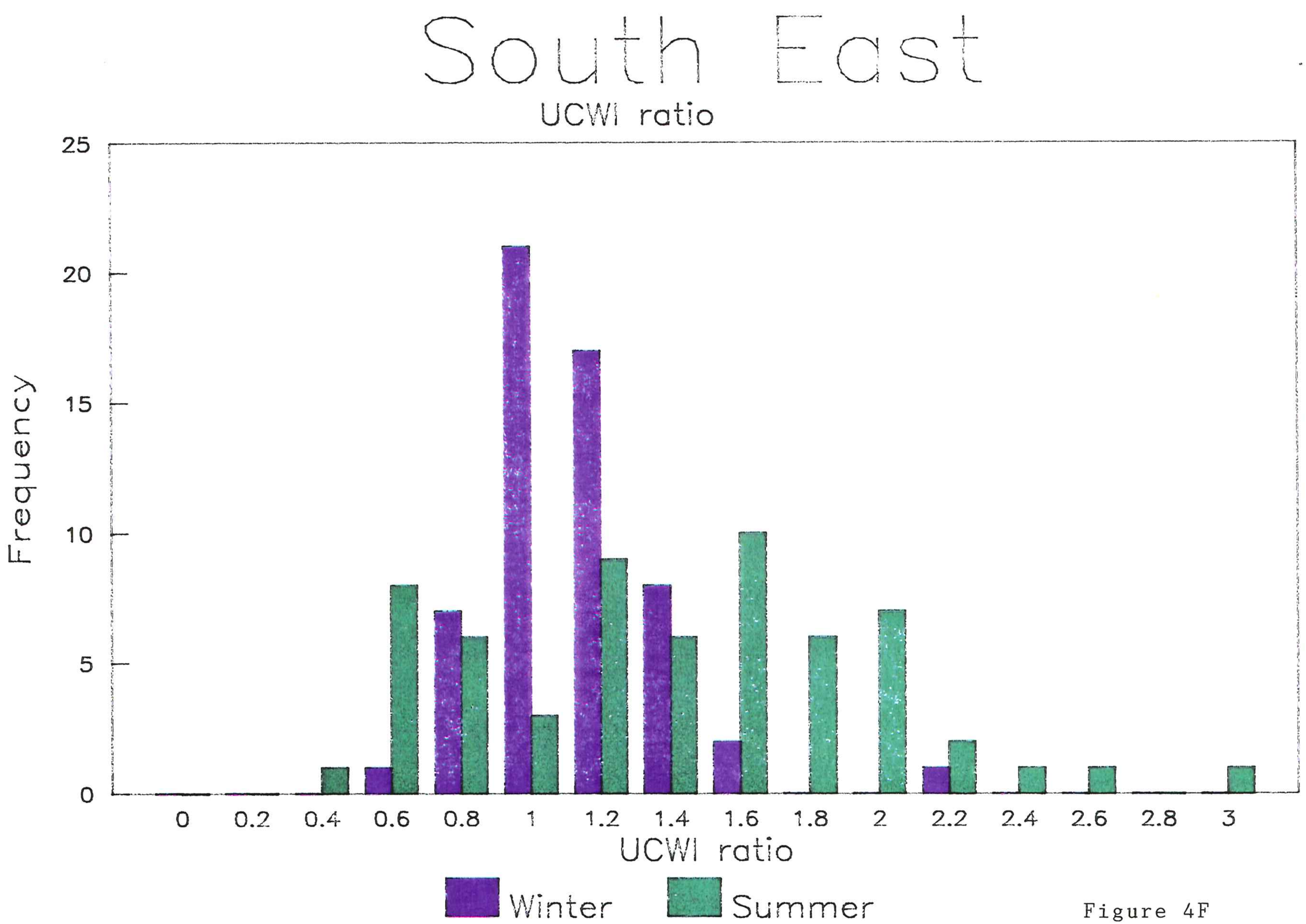
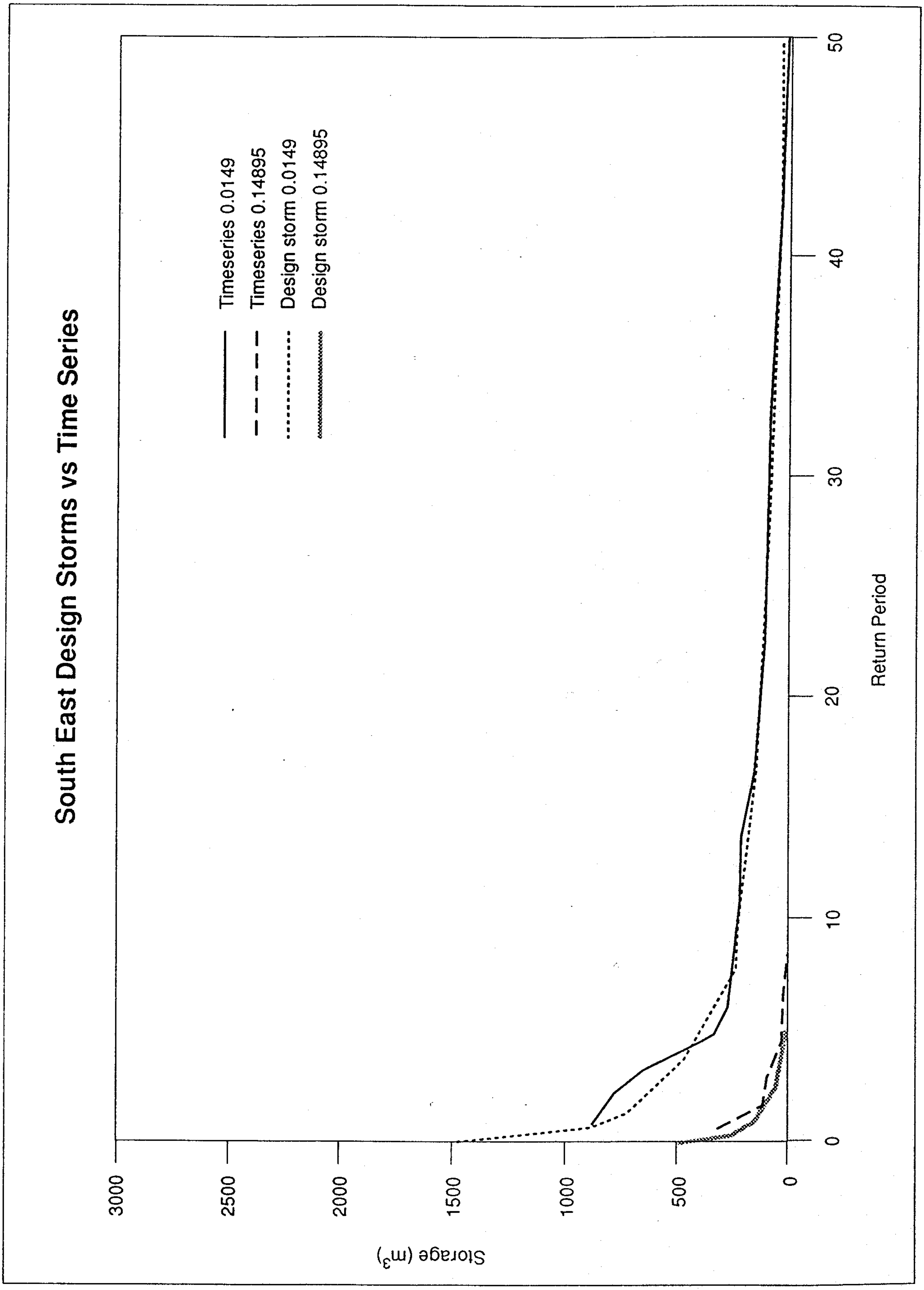
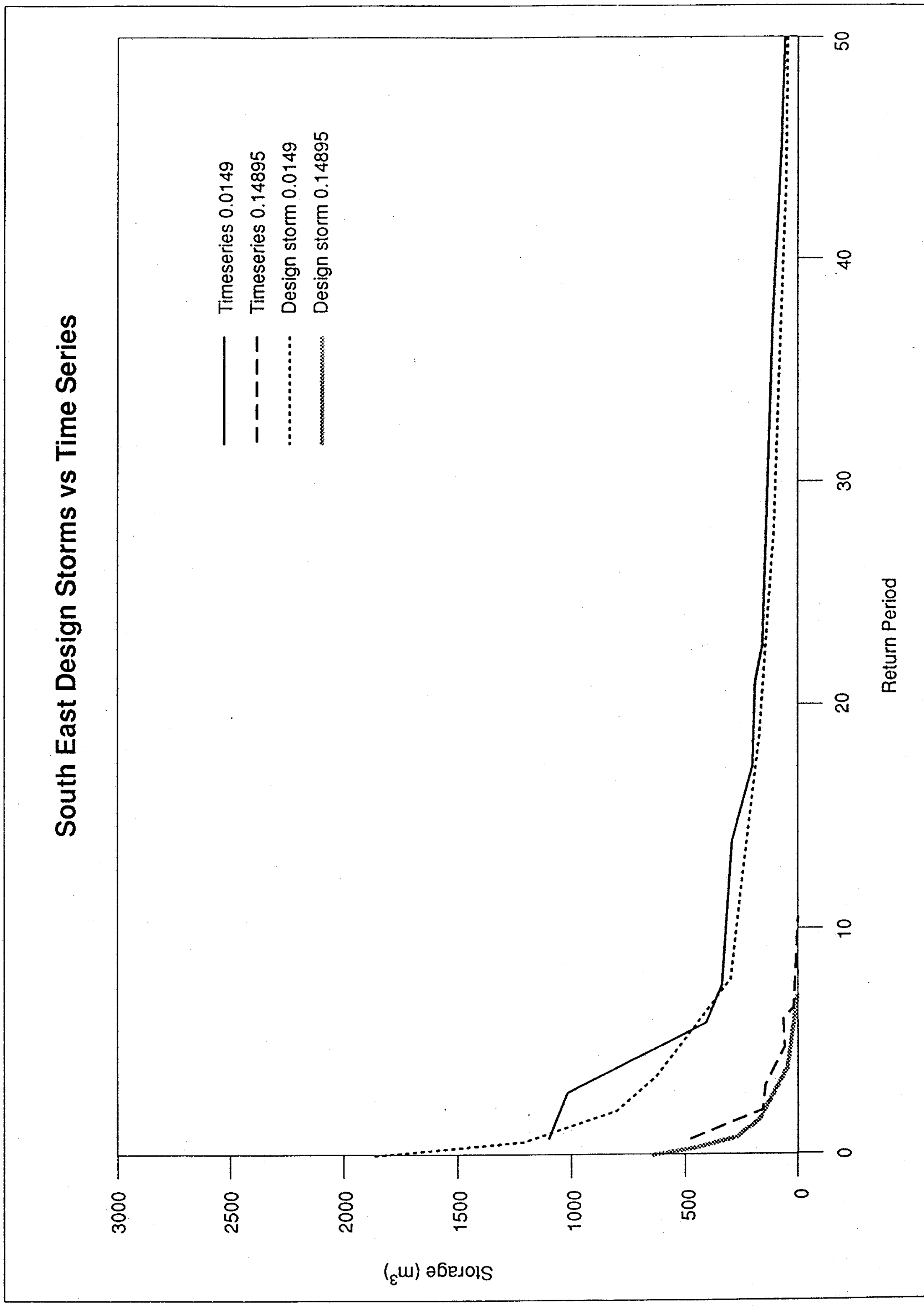

South East
UCWI ratio
Frequency
25
20
15
10
5
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
UCWI ratio
Winter
Summer

Figure 4F



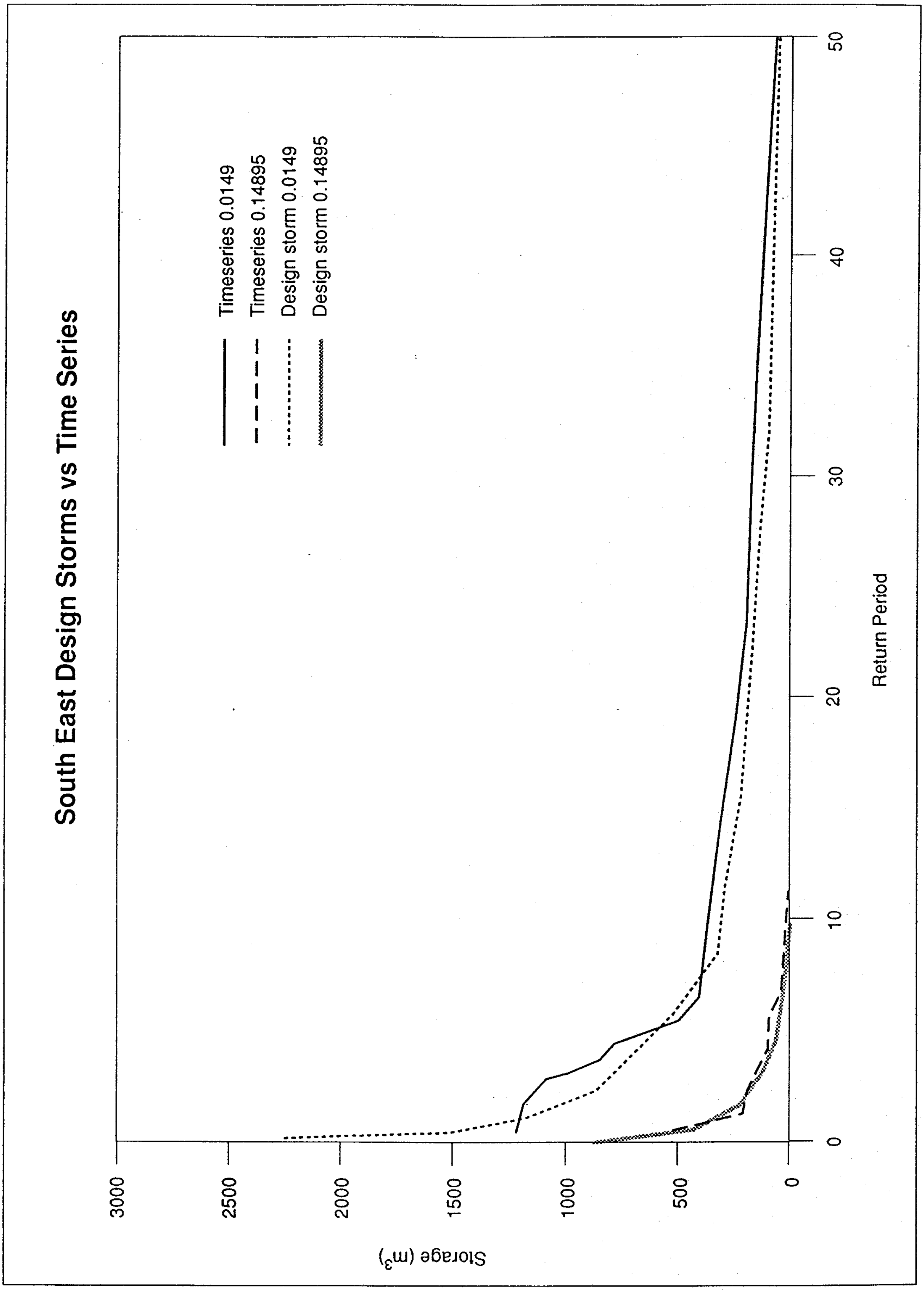
30% pervious catchment winter UCWI, peakedness varying with duration, Design storms 16hrs

FIGURE 5



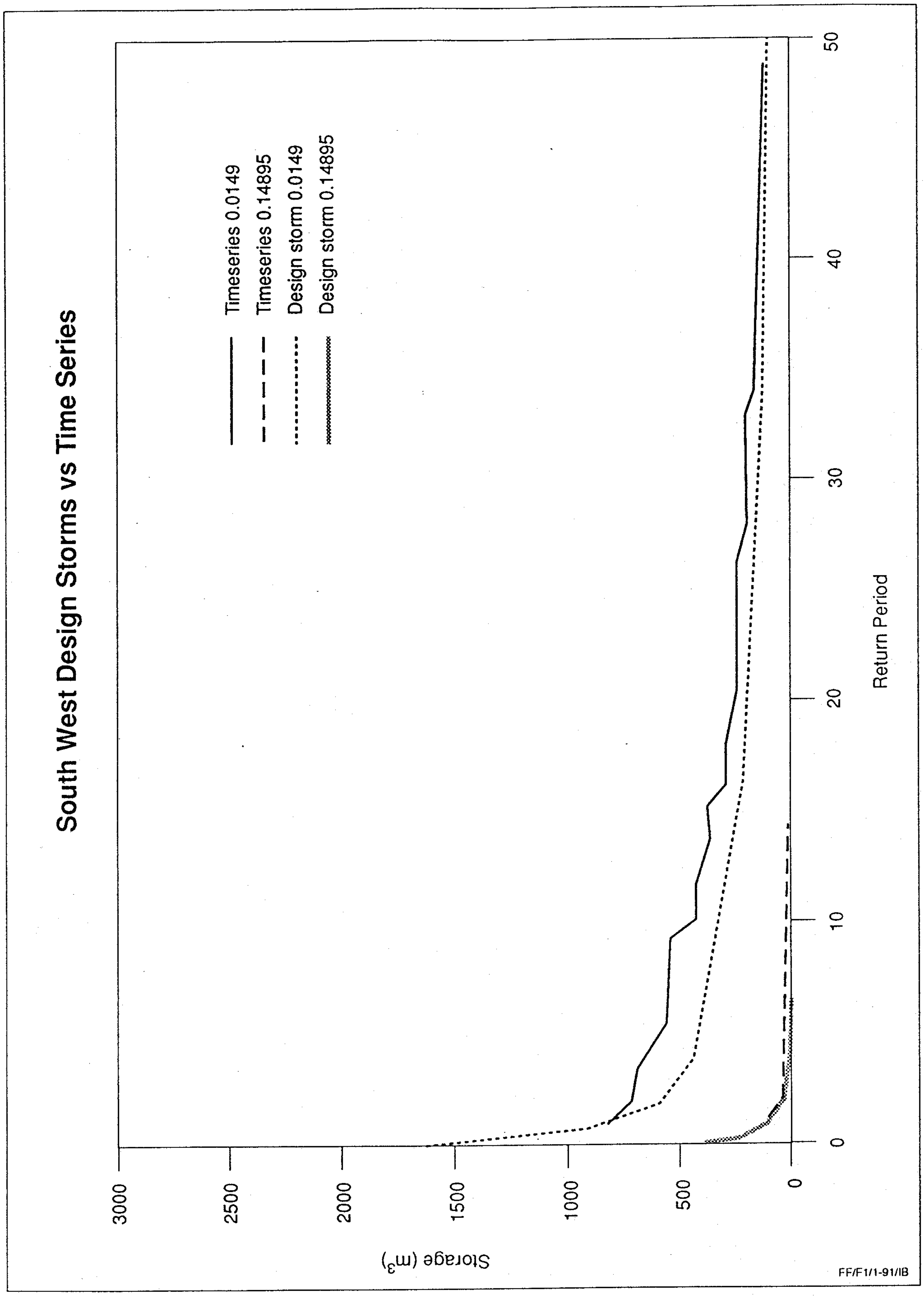
60% pervious catchment winter UCWI, peakedness varying with duration, Design storms 16

FIGURE



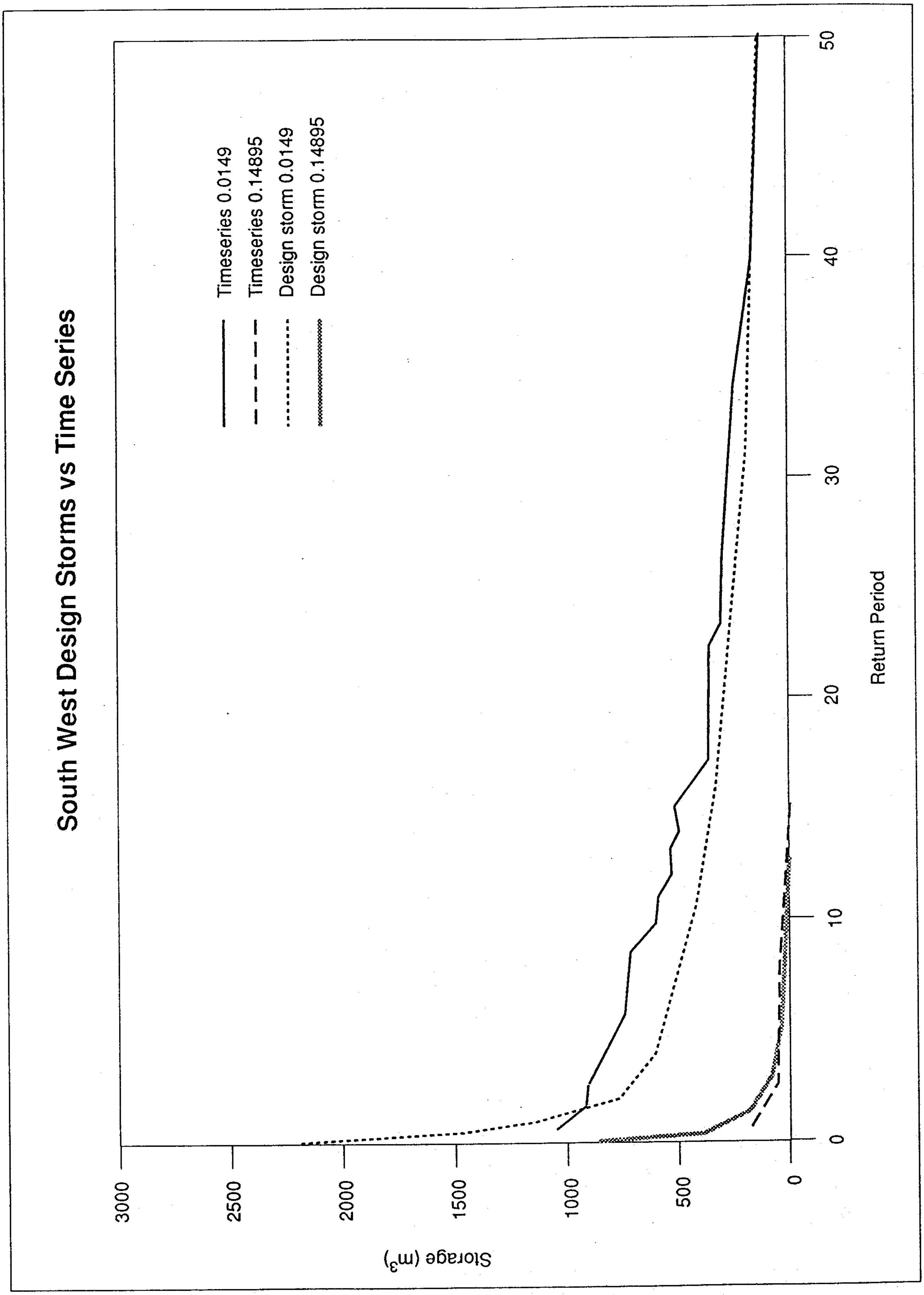
70% pervious catchment winter UCWI, peakedness varying with duration, Design storms 16hrs

FIGURE 7



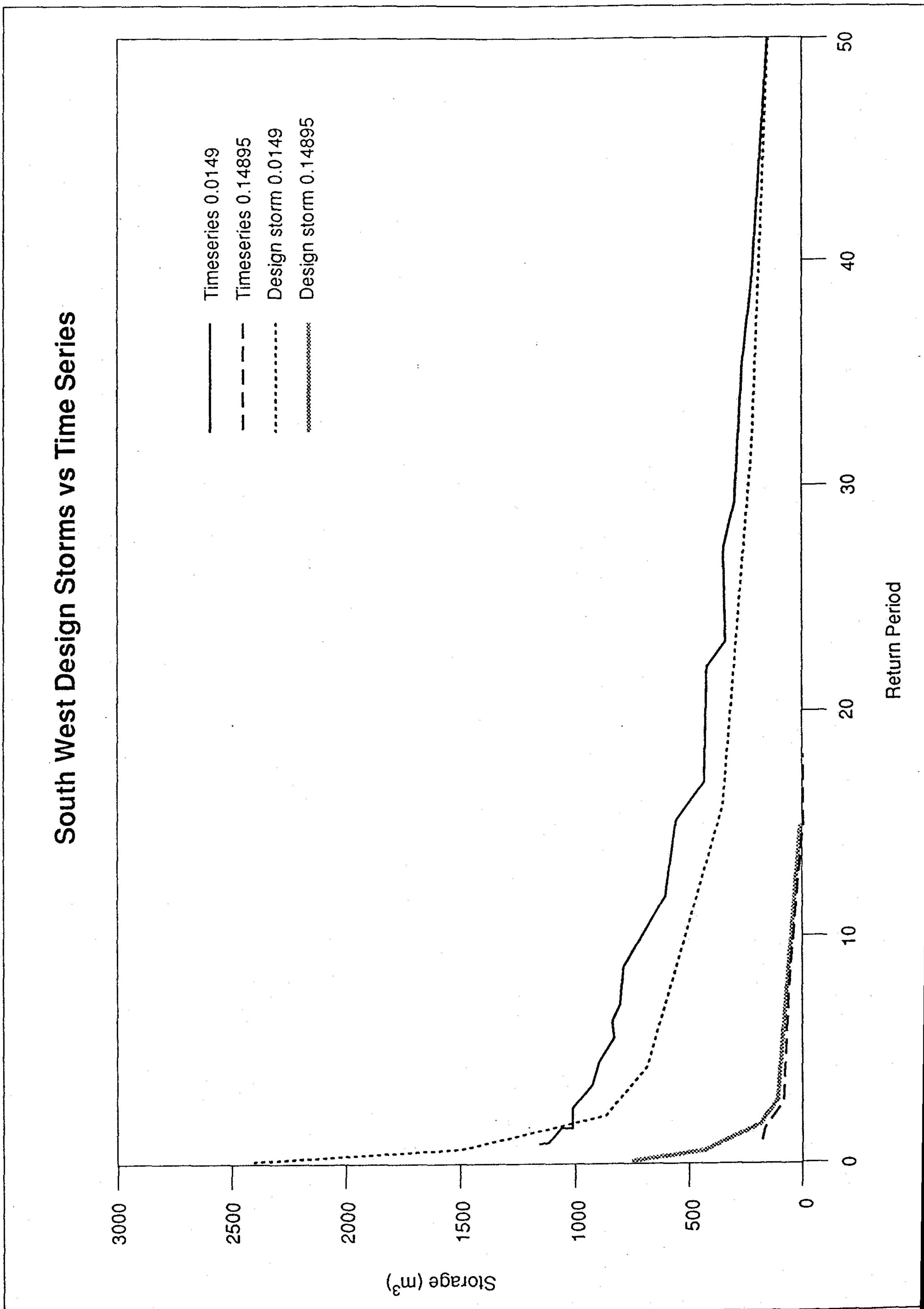
30% pervious catchment winter UCWI, peakedness varying with duration, Design storms 16h

FIGURE



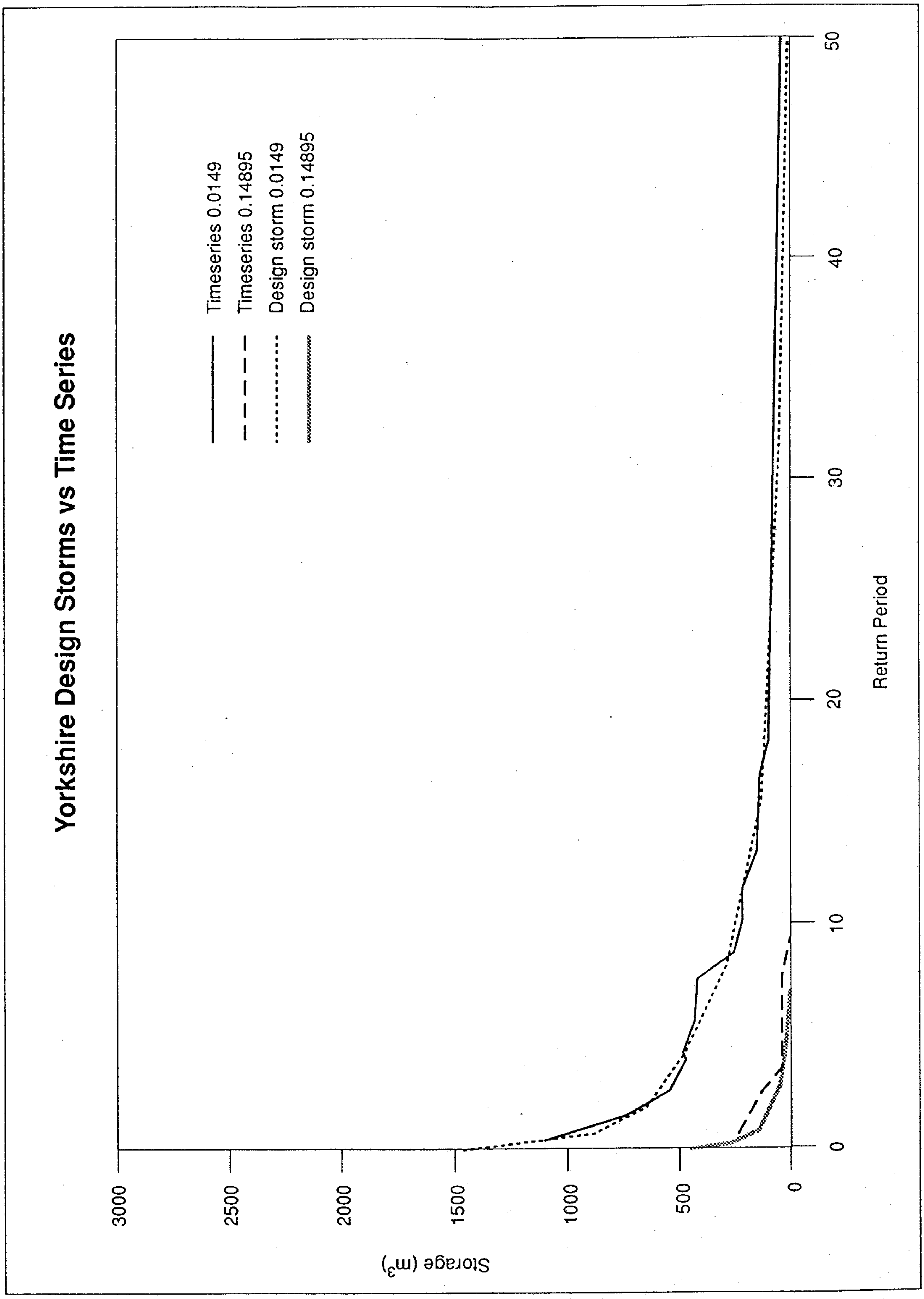
60% pervious catchment winter UCWI, peakedness varying with duration, Design storms 16hrs

FIGURE 9



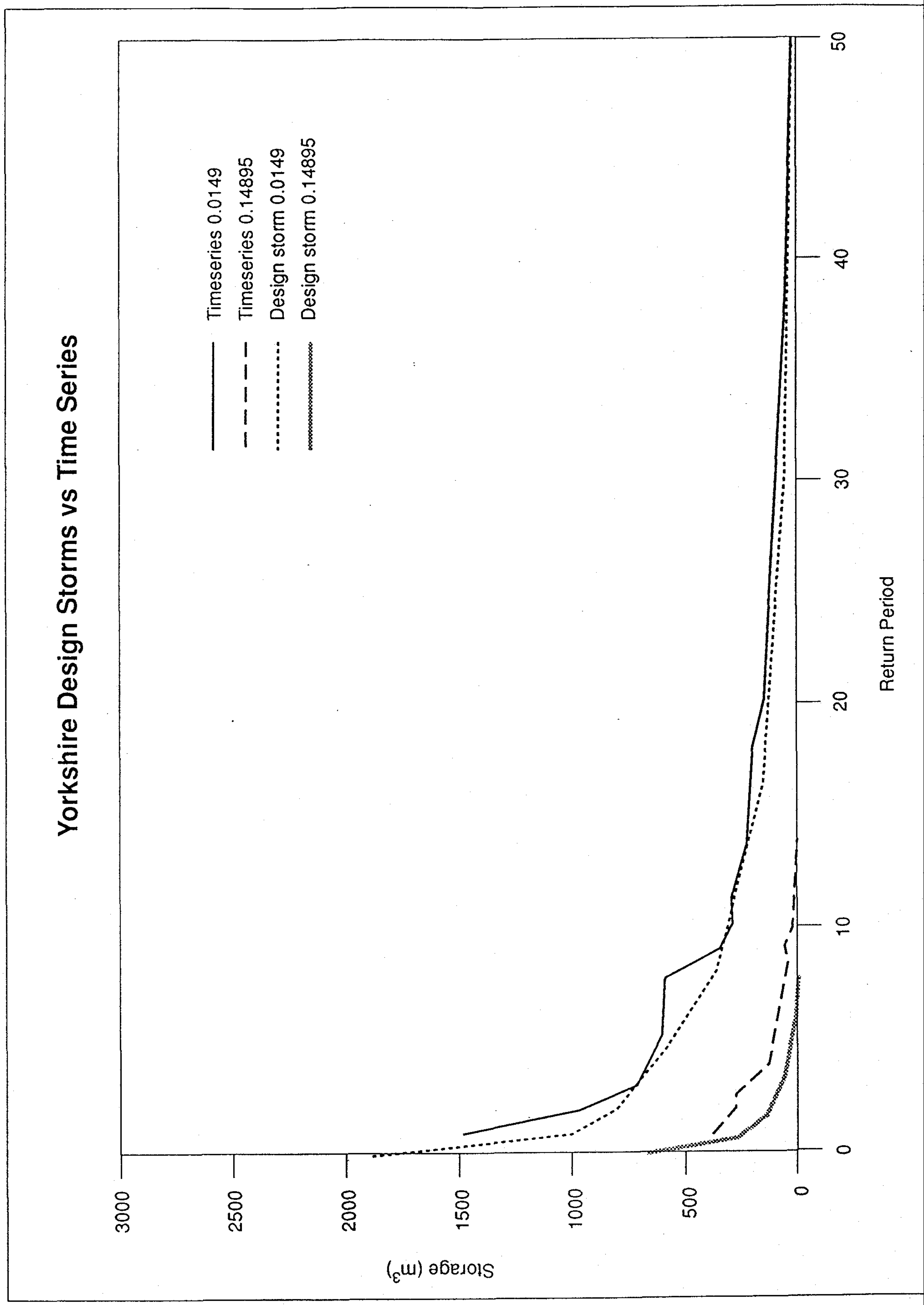
70% pervious catchment winter UCWI, peakedness varying with duration, Design storms 1

FIGURE



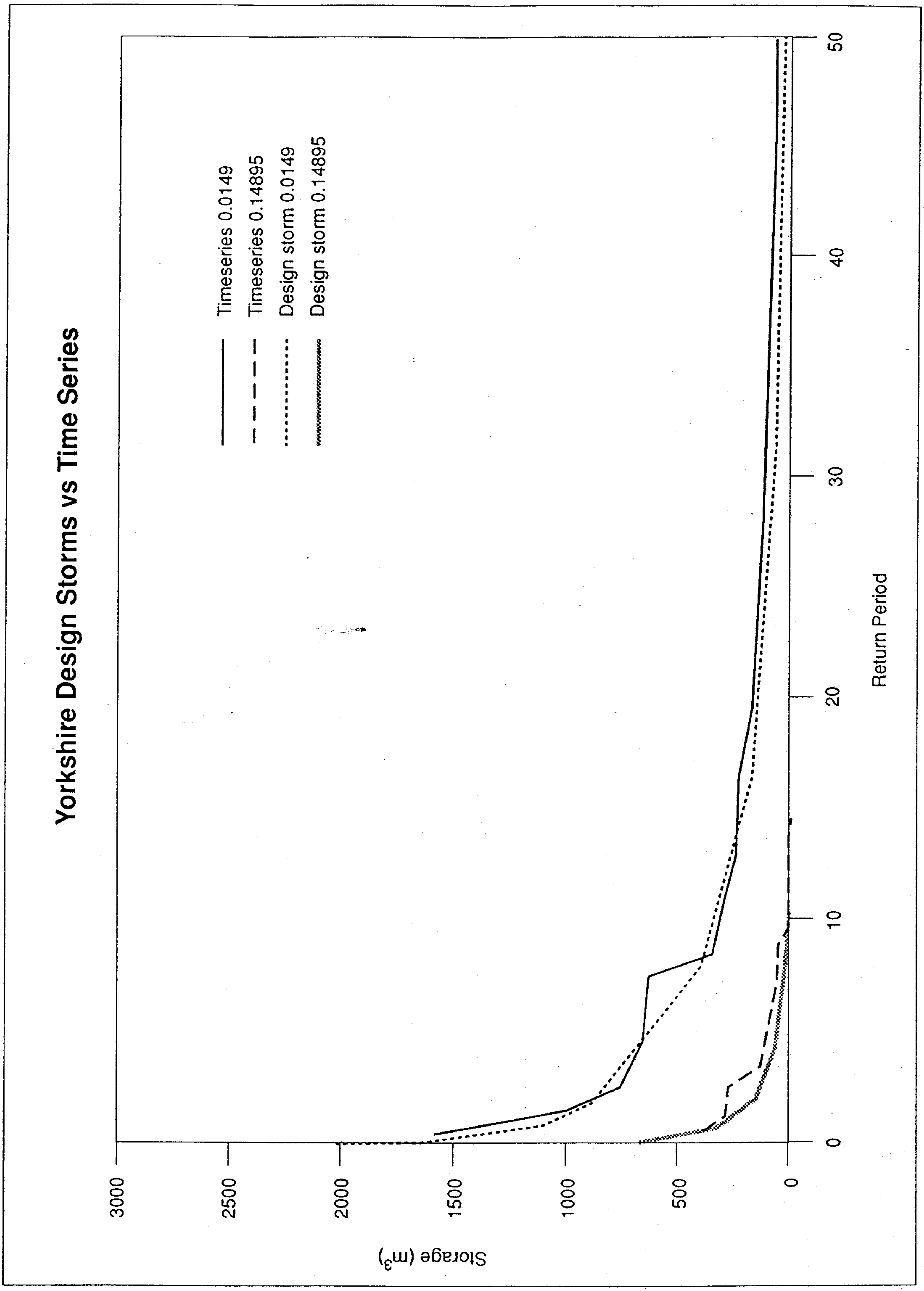
30% pervious catchment winter UCWI, peakedness varying with duration, Design storms 16hrs

FIGURE 11



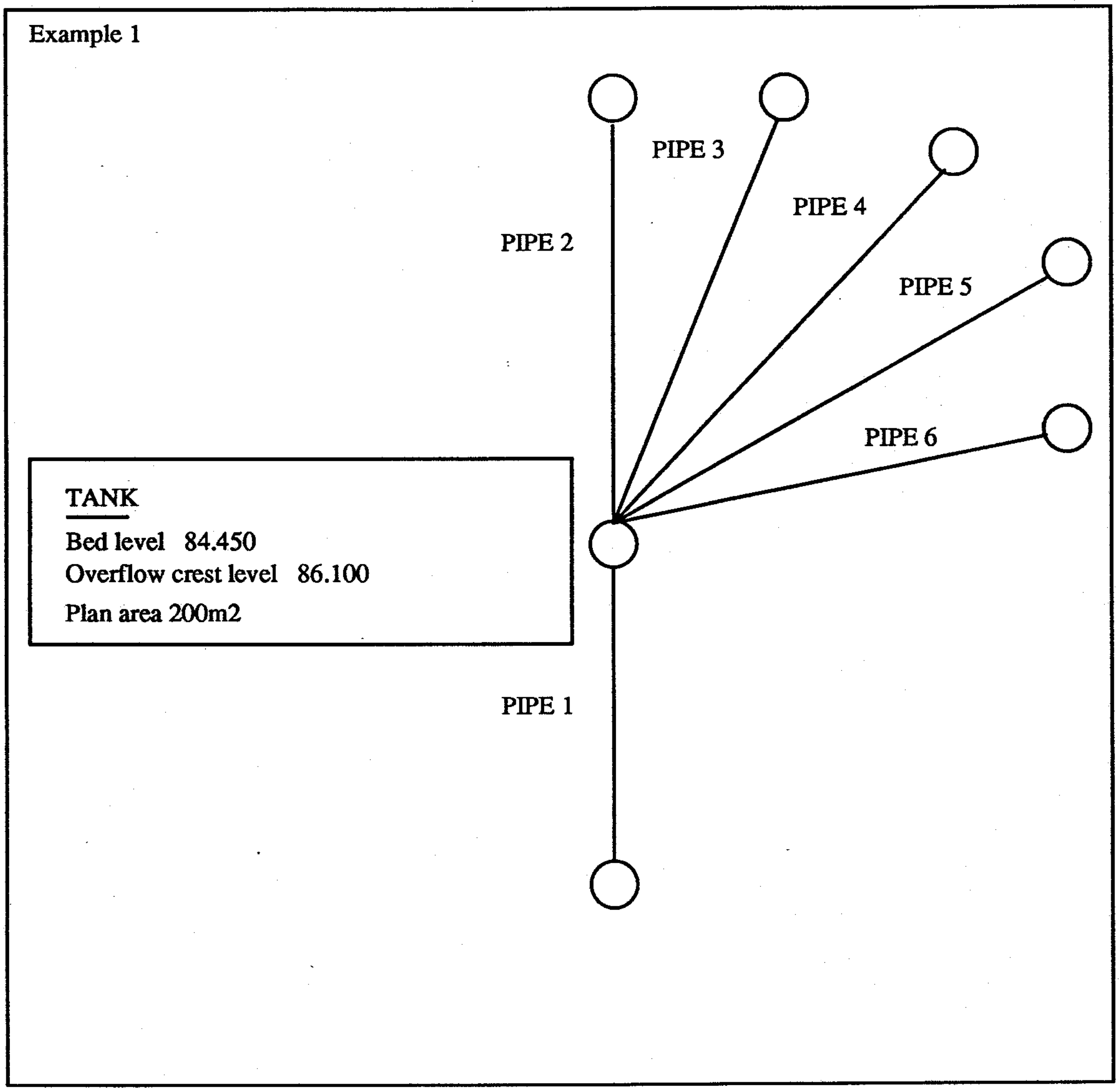
60% pervious catchment winter UCWI, peakedness varying with duration, Design storms 16

FIGURE



70% pervious catchment winter UCWI, peakedness varying with duration, Design storms 16hrs

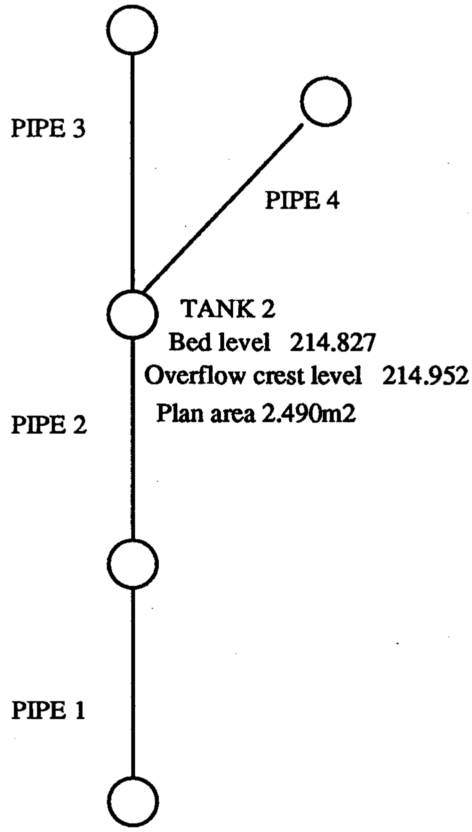
FIGURE 13



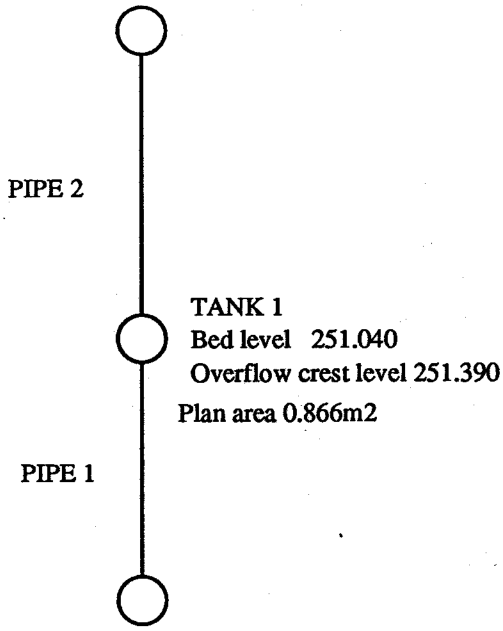
			SOFFIT LEVEL AD		AREA ha		
PIPE	DIAMETER	LENGTH	UPSTREAM	DOWNSTREAM	PAVED	ROOF	PERVIOUS
1	500	8	84.960	84.930	47.672	0	453.603
2	685	35	85.715	85.135	23.652	0	39.8
3	900	30	85.600	85.350	18.454	0	413.136
4	450	500	86.450	84.900	1.336	0	0.014
5	300	20	85.300	84.750	0.99	0	0.01
6	525	160	86.635	84.975	3.24	0	0.643

Figure 14

Example 2a



Example 2b



Example 2a

			SOFFIT LEVEL AD		AREA ha		
PIPE	DIAMETER	LENGTH	UPSTREAM	DOWNSTREAM	PAVED	ROOF	PERVIOUS
1	225	95	215.052	210.811	5.332	4.784	16.837
2	750	10	215.451	215.580	5.332	4.784	16.837
3	750	115	217.940	215.451	5.312	4.764	16.777
4	225	19	218.767	215.055	0.020	0.020	0.060

Example 2b

			SOFFIT LEVEL AD		AREA ha		
PIPE	DIAMETER	LENGTH	UPSTREAM	DOWNSTREAM	PAVED	ROOF	PERVIOUS
1	300	75	251.390	248.900	0.877	0.795	2.949
2	300	13	252.40	251.390	0.787	0.755	2.879

Figure 15

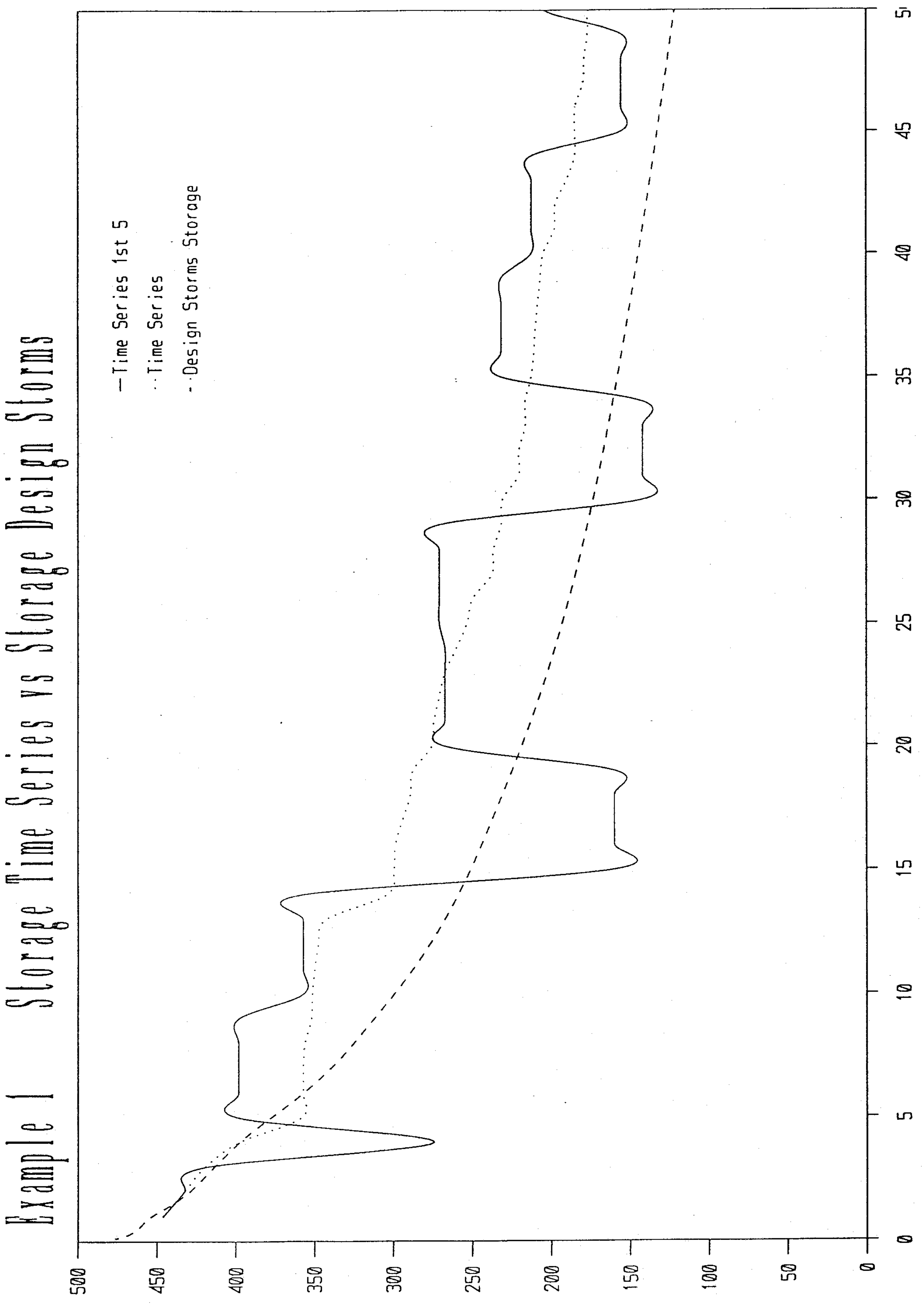

Example 1 Storage Time Series vs Storage Design Storms
—Time Series 1st 5
· · Time Series
- - Design Storms Storage
0
50
100
150
200
250
300
350
400
450
500
0
5
10
15
20
25
30
35
40
45
50
Return Period
Storage m3

FIGURE 16

Example 1 Overflow Time Series vs Overflow Design Storms

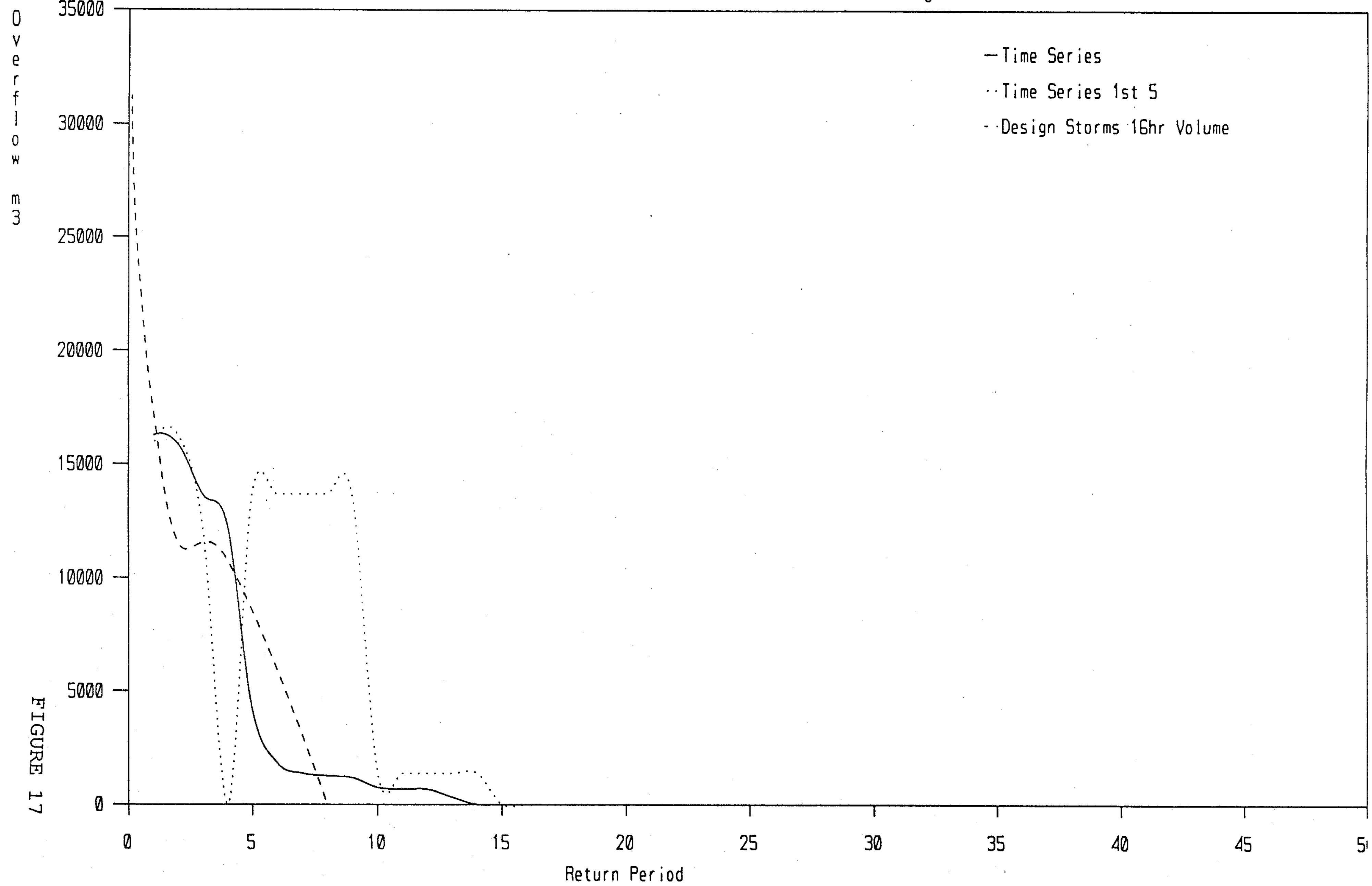


FIGURE 17

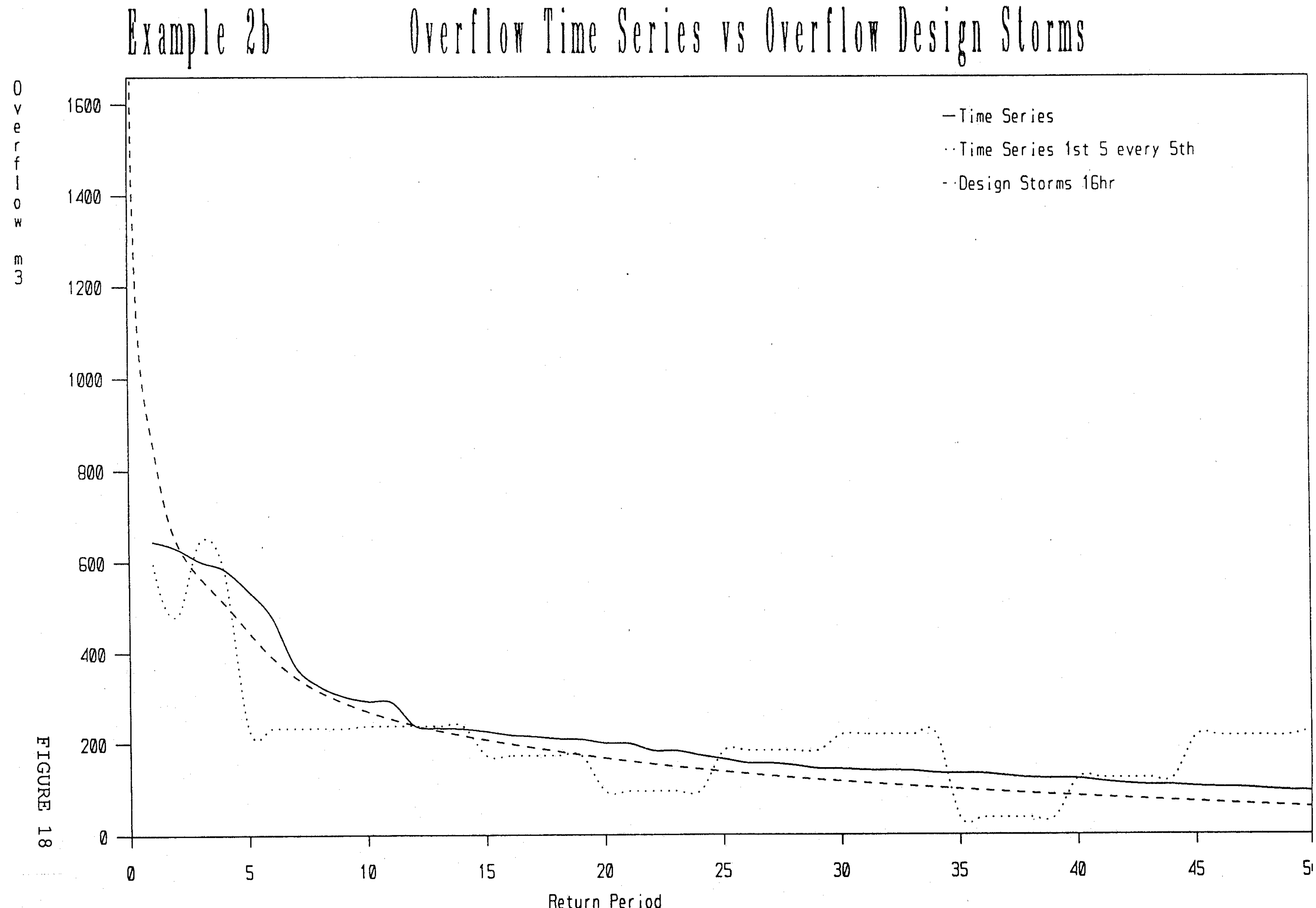

Example 2b
Overflow Time Series vs Overflow Design Storms
Overflow m3
1600
1400
1200
1000
800
600
400
200
0
—Time Series
··Time Series 1st 5 every 5th
- ·Design Storms 16hr
0
5
10
15
20
25
30
35
40
45
50
Return Period

FIGURE 18

APPENDIX A

Annual Series Rainfall Data for SOUTH EAST U.K.   **** RANKED YEAR ****

```
        3    15     F     F     F     0     0
             3.0
UCWI=90   **   1 ** EVENT  4 (AUG)      14:41  4/8/71            320 VALUES
             0.30          90           1
         90     60   350  600
  9.000    0.000    1.000    2.000    3.000    4.000    5.000    6.000    7.000    8.000
 19.000   10.000   11.000   12.000   13.000   14.000   15.000   16.000   17.000   18.000
 29.000   20.000   21.000   22.000   23.000   24.000   25.000   26.000   27.000   28.000
 39.000   30.000   31.000   32.000   33.000   34.000   35.000   36.000   37.000   38.000
 49.000   40.000   41.000   42.000   43.000   44.000   45.000   46.000   47.000   48.000
 59.000   50.000   51.000   52.000   53.000   54.000   55.000   56.000   57.000   58.000
 69.000   60.000   61.000   62.000   63.000   64.000   65.000   66.000   67.000   68.000
  0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
  0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
UCWI=146   ** 2 ** EVENT  3 (APR)      01:07  5/4/58                380 VALUES
             0.30          146          1
         90     60   360  600
 61.000   70.000   69.000   68.000   67.000   66.000   65.000   64.000   63.000   62.000
 51.000   60.000   59.000   58.000   57.000   56.000   55.000   54.000   53.000   52.000
 41.000   50.000   49.000   48.000   47.000   46.000   45.000   44.000   43.000   42.000
 31.000   40.000   39.000   38.000   37.000   36.000   35.000   34.000   33.000   32.000
 21.000   30.000   29.000   28.000   27.000   26.000   25.000   24.000   23.000   22.000
 11.000   20.000   19.000   18.000   17.000   16.000   15.000   14.000   13.000   12.000
  1.000   10.000    9.000    8.000    7.000    6.000    5.000    4.000    3.000    2.000
  0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
  0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
UCWI=65 **   3 ** EVENT 15 (SEP)      08:01  25/9/67               610 VALUES
        0.30          65           1
  160    60   480   600
  9.000    0.000    1.000    2.000    3.000    4.000    5.000    6.000    7.000    8.000
 19.000   10.000   11.000   12.000   13.000   14.000   15.000   16.000   17.000   18.000
 29.000   20.000   21.000   22.000   23.000   24.000   25.000   26.000   27.000   28.000
 39.000   30.000   31.000   32.000   33.000   34.000   35.000   36.000   37.000   38.000
 49.000   40.000   41.000   42.000   43.000   44.000   45.000   46.000   47.000   48.000
 59.000   50.000   51.000   52.000   53.000   54.000   55.000   56.000   57.000   58.000
 69.000   60.000   61.000   62.000   63.000   64.000   65.000   66.000   67.000   68.000
 61.000   70.000   69.000   68.000   67.000   66.000   65.000   64.000   63.000   62.000
 51.000   60.000   59.000   58.000   57.000   56.000   55.000   54.000   53.000   52.000
 41.000   50.000   49.000   48.000   47.000   46.000   45.000   44.000   43.000   42.000
 31.000   40.000   39.000   38.000   37.000   36.000   35.000   34.000   33.000   32.000
 21.000   30.000   29.000   28.000   27.000   26.000   25.000   24.000   23.000   22.000
 11.000   20.000   19.000   18.000   17.000   16.000   15.000   14.000   13.000   12.000
  1.000   10.000    9.000    8.000    7.000    6.000    5.000    4.000    3.000    2.000
  0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
  0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
```