Institute of Hydrology

Rainfall patterns over London

Final Report

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Natural Environment Research Council

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**This Report is prepared for the National Rivers Authority
Thames Region**

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Executive Summary

A Precision Encoder and Pattern Recognition (PEPR) System at the University of Oxford Nuclear Physics Laboratory was employed during the 1970's for digitising some 350,000 rainfall charts from 77 raingauges over the London area. Until now, the resulting PEPR data set has been subject to little analysis. Recent interest in its use stemmed from a need to gain a better understanding of the variability of rainfall in both space and time in support of flood defence responsibilities over the London metropolitan area. The longevity of some records, one dating back to 1928 (albeit with a gap of 16 years), could prove useful for identifying long-term temporal trends in rainfall. Similarly, the density of the network of roughly one gauge every 30 km^2 over an area of 2,200 km^2 could provide evidence of patterns of rainfall that might have important implications for a flood defence strategy for the capital.

The report begins with an overview of the PEPR database and provides a quantitative overview of the record using seasonal data tables supported by graphical displays. This also serves to reveal problems with missing and unreliable data in the record which are addressed in detail in the report's Appendix. An analysis of notable storm events affecting London, through the mapping of storm total isohyets and the display of storm profiles, fails to reveal preferential areas for storm development and indicates a variety of profile shapes, including a number that are double-peaked. A detailed characterisation of the rainfall time series into dry and wet spells allows distribution functions to be fitted to storm duration and magnitude and to the average shape of storm profiles. Mapping of the parameters of these distributions yields useful insights into the pattern of storms over London.

Having first corrected the PEPR data set as far as possible to properly identify data that are missing, attention is turned to frequency-based analyses of the rainfall records. Classical depth-duration-frequency (DDF) analysis for individual gauge records is complemented by mapping of the Generalised Extreme Value distribution parameters fitted to the DDF data for all 77 gauge records, in a search for spatial patterns. An extension of the above analyses, which employ hourly data from the PEPR database, to consider sub-hourly amounts is then undertaken. The form of analysis follows closely the Bilham approach developed in 1935 which involves a daily count of rainfalls of a given depth and duration. Results very similar to those of Bilham are obtained for the London area.

Finally, an operational application of the PEPR dataset is considered in which a conditional rainfall forecast technique, based on Markov chain theory, is developed and evaluated for use in flood forecasting and warning. The technique not only provides a simple means of forecasting rainfall but also provides an assessment of the risk of exceedence, possibly conditional on different synoptic conditions occurring.

Acknowledgements

The members of the Steering Committee of the Rainfall Patterns over London Study - Chris Haggett, George Merrick, Ged Kennedy and Bryony May of the National Rivers Authority Thames Region - are thanked for their support and contributions to the project. Particular acknowledgement is due to Chris Haggett in recognising the potential value of the PEPR data set in gaining a better understanding of variations in rainfall over London: this data set has previously been subject to little analysis, despite the not inconsiderable investment involved in its creation.

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1. Introduction

A better understanding of the spatial and temporal variations of rainfall over London could be of significant benefit to the flood defence of London. Improvements in both design and operational management practices concerned with minimising flood damage could result from a better knowledge of rainfall variability over the metropolitan area. An ideal opportunity to analyse rainfall variability over London has arisen through the existence of the PEPR data set, obtained by digitising some 350,000 rainfall charts from 77 raingauges extending over the Greater London area, and in one case dating back to 1928, albeit with a gap of 16 years. This data set for London has, until now, been subject to little analysis, despite the not inconsiderable investment involved in its creation. The present report, in presenting the results of a two year study of the PEPR data set, redresses this omission and provides new insights into the variability of rainfall over London.

The PEPR data set was created as part of a collaborative study involving the former Greater London Council and the Meteorological Office. It was created using the PEPR System (Precision Encoder and Pattern Recognition System) at the University of Oxford Nuclear Physics Laboratory which was used to transcribe rainfall charts into digital values with a machine precision of .01 mm and having a time resolution of up to one minute. Timing errors, due to clock drift and manual chart changing, could be as great as 15 minutes so that the absolute accuracy might be significantly less. A thorough assessment of the quality of the data is reported in Appendix A.

The extent of the PEPR data set and the database created at IH to access it are outlined in Section 2. A broad view of the data is accomplished in Section 3 using exploratory data analysis tools in the form of seasonal data tables and graphical displays; this includes an assessment of the extent and nature of missing data. A search for preferential areas for storm development, based on a detailed mapping of notable storm events over London, is reported in Section 4. This is complemented in Section 5 by an analysis involving all storms using parameter distributions fitted to storm characteristics, such as storm duration and magnitude, to investigate the spatial variability of storm features over London. The next two sections deal with frequency analysis of the PEPR record. Isohyetal maps for a given duration and return period are derived in Section 6. Section 7 presents a Bilham-type analysis of sub-hourly rainfall amounts, obtaining the number of days when rainfall of a given depth and duration occurs. A new Bilham-type relation for London is established and related to previously developed formulae. An operational application of the PEPR dataset is investigated in Section 8 where a conditional rainfall forecasting technique, based on Markov chain theory, is formulated and evaluated for use in flood forecasting and warning. Finally, Section 9 presents a set of conclusions resulting from the Study and some suggestions for further work.

2. The PEPR data set and database

2.1 INTRODUCTION

This section begins with an overview of the PEPR data set, presenting the original tabulation of the extent of the data and a substantial revision following the quality control reported in Appendix A. This is followed by a detailed account of the creation of the PEPR database on the mainframe computer at the Institute of Hydrology. A PC-compatible form of this database has been developed and provided to the NRA Thames Region, in response to a request during the course of the Study.

2.2 THE PEPR DATA SET

The PEPR data set contains rainfall records for 77 raingauges within the London area. Whilst 134 raingauges were originally identified, 52 of these made no reference to available data and a further 5 contained no data during the dates given. The location of the 77 raingauges are shown in Figure 2.1 and Table 2.1 provides a summary of the period of record for each gauge. This Table was revised during the course of the project to better reflect the periods for which data are actually available: this is presented as Table 2.2. However, anomalous 'dry' months (Appendix A) are still included in this revised table. Note that two particularly long records exist: at Hayes, Wood End Nurseries for 47 years from 1928 to 1974 (but with a gap of 16 years from 1945 to 1960) and at Hampstead for 43 years from 1933 to 1975.

2.3 THE IH PEPR DATABASE

The magnetic tape containing the PEPR data for raingauge stations located within what was formerly the Greater London Council (GLC) area was supplied to IH by NRA Thames Region. A duplicate was made and the original returned to the NRA. The tape had been prepared some years previous as a backup/copy on the GLC's IBM computer: this process had introduced extra blocking in the data for which documentation was not available and it took some time to extract the original data structure from the two levels of data blocking present. In the first instance a program was written on IH's microVAX 3400 to read and list the contents of the tape. This was extended to place the data into files for transfer to the IBM 4381 at IH, which was used for the main analysis work because of the significant disk and cpu demands

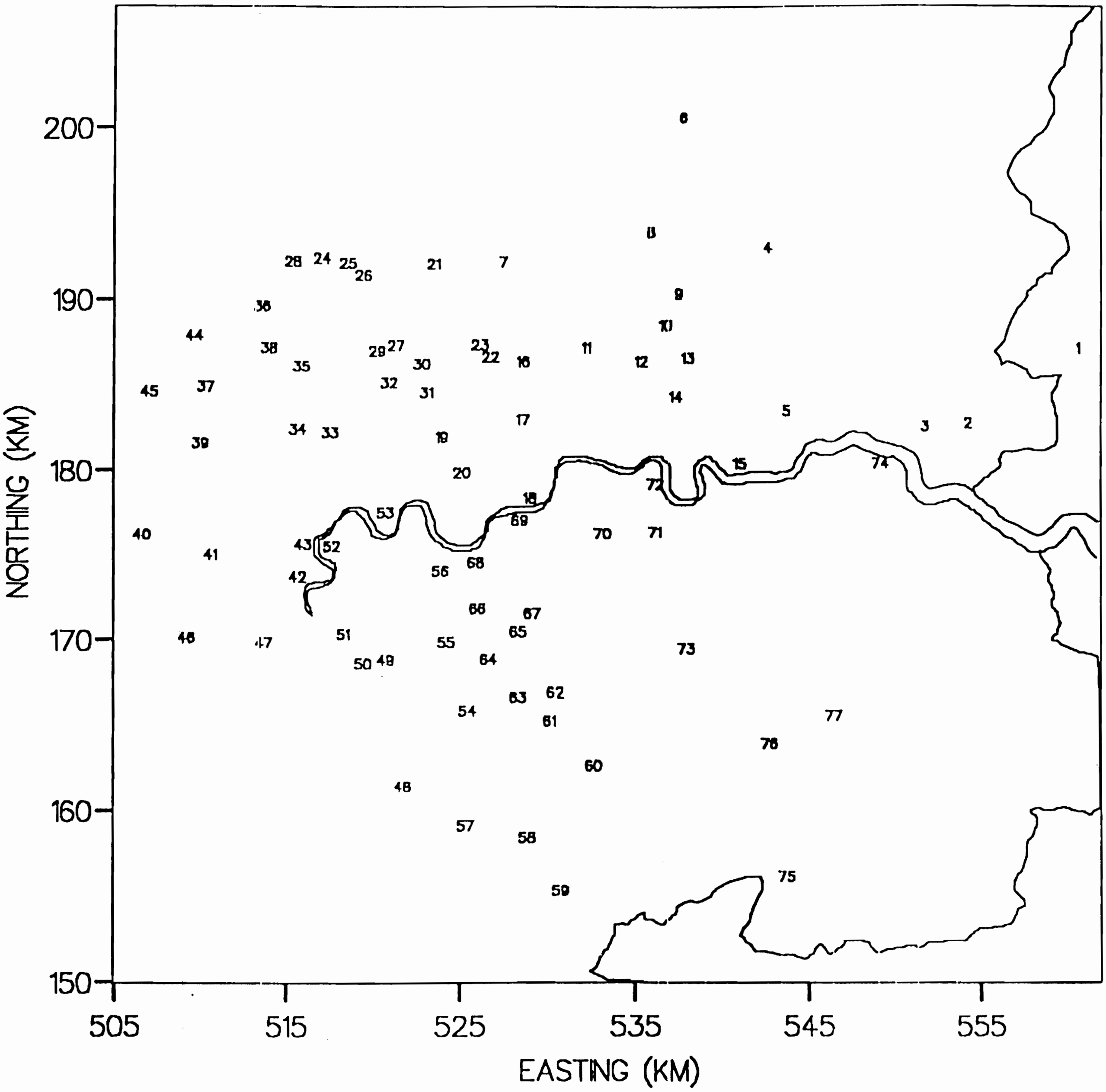


Figure 2.1 Location of PEPR rainfall stations over London

Table 2.1 Original summary of PEPR rainfall stations over London

1	BURY FARM	(01 01 1972-31 12 1976)
2	SPRING PARK FARM	(01 01 1972-31 12 1975)
3	RIVERSIDE STW	(01 01 1972-31 12 1976)
4	CHIGWELL STW	(01 01 1973-31 12 1976)
5	FOLKESTONE ROAD	(01 01 1970-31 12 1976)
6	WALTHAM ABBEY	(01 01 1972-31 12 1976)
7	MUSWELL HILL	(01 01 1958-30 11 1961),(01 01 1962-30 04 1966)
		(01 06 1966-31 12 1967),(01 01 1972-31 12 1976)
8	DEEPHAMS STW	(01 01 1972-31 12 1976)
9	WALTHAMSTOW, LLOYD PARK	(01 01 1972-31 12 1976)
10	LOWHALL FARM DEPOT	(01 01 1958-31 12 1976)
11	GREEN LANES	(01 01 1963-31 01 1963),(01 03 1963-31 12 1976)
12	CLAPTON POND	(01 01 1960-31 12 1960),(01 03 1961-30 11 1964)
		(01 01 1965-31 12 1976)
13	AUCKLAND ROAD PS	(01 01 1971-31 12 1976)
14	WICK LANE	(01 01 1971-31 12 1974)
15	LYLE PARK	(01 01 1973-31 12 1976)
16	PARLIAMENT HILL	(01 01 1974-31 12 1976)
17	REGENTS PARK	(01 01 1973-31 07 1974),(01 09 1974-31 12 1974)
18	WESTERN PS	(01 01 1963-31 12 1976)
19	KENSINGTON MEMORIAL GDNS	(01 01 1974-31 12 1976)
20	HOLLAND PARK	(01 01 1972-31 12 1976)
21	MILL HILL	(01 01 1960-31 12 1976)
22	HAMPSTEAD	(01 01 1933-31 12 1975)
23	GOLDERS HILL PARK	(01 01 1976-31 12 1976)
24	STANMORE	(01 01 1942-31 12 1971)
25	CANONS PARK	(01 01 1973-28 02 1973),(01 04 1973-31 12 1976)
26	CHANDOS RECREATION GRND	(01 01 1942-30 09 1973),(01 01 1957-31 12 1960)
27	BRENT RESERVOIR	(01 01 1948-31 03 1948),(01 01 1949-31 12 1950)
		(01 01 1953-31 12 1976)
28	HARROW WEALD CEMETERY	(01 01 1972-31 12 1976)
29	WEMBLEY	(01 01 1964-31 12 1969)
30	GLADSTONE PARK I	(01 01 1969-31 12 1975)
31	WILLESDEN WORKS	(01 01 1972-31 12 1976)
32	STONEBRIDGE PARK	(01 01 1966-31 12 1975)
33	EALING CASTLEBAR	(01 01 1962-28 02 1974),(01 04 1974-31 12 1976)
34	BRENTSIDE SCHOOL	(01 01 1961-19 08 1971)
35	SUDBURY HILL P.S.	(01 01 1953-31 12 1956)
36	PINNER CEMETERY	(01 01 1957-31 12 1961)
37	NORTHOLT AERODROME	(01 01 1946-31 12 1973)
38	NEWTON PARK DEPOT	(01 01 1975-31 12 1976)
39	HAYES, WOOD END NURSERIES	(01 01 1928-31 12 1944),(01 01 1961-31 12 1974)
40	PERRY OAKS	(01 01 1972-31 12 1976)
41	HATTON NURSERIES	(01 01 1973-31 12 1976)
42	TWICKENHAM STW	(01 01 1941-31 12 1945)
43	MOGDEN STW	(01 01 1969-31 12 1976)
44	RUISLIP	(01 01 1944-31 12 1956),(02 01 1957-08 09 1970)
		(02 01 1957-31 12 1976)
45	UXBRIDGE, HONEYCROFT NRS	(01 01 1974-31 12 1976)
46	ASHFORD COMMON	(01 01 1972-31 12 1976)
47	HAMPTON	(01 01 1954-31 12 1974)
48	EPSOM WATER WORKS	(01 01 1971-30 07 1971),(01 08 1971-31 12 1974)
49	MALDEN STW	(01 01 1957-31 05 1957),(01 08 1957-31 12 1966)
50	HOGSMILL STW	(01 01 1957-27 11 1965),(30 11 1965-31 12 1976)
51	CANBURY GARDENS	(01 01 1948-09 12 1952),(11 12 1952-11 12 1952)
		(19 12 1952-19 12 1952),(21 12 1952-21 12 1952)
		(29 12 1952-29 12 1952),(31 12 1952-31 08 1960)
		(02 09 1960-02 09 1960),(04 09 1960-05 09 1960)

Table 2.1 continued ***Original summary of PEPR rainfall stations over London***

	(07 09 1960-13 09 1960),(17 09 1960-31 12 1961)
	(01 01 1963-01 08 1963),(05 08 1963-08 08 1963)
	(11 08 1963-14 08 1963),(18 08 1963-19 08 1963)
	(22 08 1963-22 08 1963),(24 08 1963-24 08 1963)
	(28 08 1963-28 08 1963),(30 08 1963-30 08 1963)
	(01 09 1963-31 12 1976)
52 KEW OBSERVATORY	(01 01 1944-31 12 1974)
53 KEW STW	(01 01 1966-28 02 1966),(01 04 1966-31 12 1976)
54 SUTTON STW	(01 01 1936-31 03 1936),(01 05 1936-31 12 1974)
55 RAYNES PARK PS	(01 01 1960-31 12 1961),(01 01 1964-31 12 1976)
56 PUTNEY HEATH	(01 01 1964-31 12 1976)
57 BANSTEAD	(01 01 1967-31 12 1974)
58 HOW GREEN RESERVOIR	(01 01 1972-31 12 1976)
59 ALDERSTEAD HEATH	(01 01 1962-31 12 1968)
60 PURLEY OAKS	(01 01 1965-29 11 1972)
61 BEDDINGTON PARK	(01 01 1962-28 02 1963),(01 04 1963-31 12 1964)
62 BEDDINGTON STW	(01 01 1972-31 12 1976)
63 CARSHALTON PS	(01 01 1965-31 12 1971)
64 MORDEN HALL	(01 01 1960-05 04 1965),(07 04 1965-07 04 1965)
	(12 04 1965-16 04 1965),(19 04 1965-25 04 1965)
	(29 04 1965-01 05 1965),(03 05 1965-31 05 1965)
	(02 06 1965-06 06 1965),(08 06 1965-10 06 1965)
	(13 06 1965-15 06 1965),(18 06 1965-20 06 1965)
	(22 06 1965-04 07 1966),(06 07 1966-09 07 1966)
	(11 07 1966-14 07 1966),(16 07 1966-17 07 1966)
	(22 07 1966-23 07 1966),(25 07 1966-25 07 1966)
	(27 07 1966-29 07 1966),(01 08 1966-31 12 1976)
65 LONDON ROAD	(01 01 1965-31 12 1976)
66 GAP ROAD CEMETERY	(01 01 1972-31 12 1976)
67 FURZEDOWN RECREATION GRD	(01 01 1974-31 12 1976)
68 KING GEORGE'S PARK	(01 01 1974-31 12 1976)
69 BATTERSEA PARK	(01 01 1974-31 12 1976)
70 RUSKIN PARK	(01 01 1974-31 12 1976)
71 TELEGRAPH HILL	(01 01 1974-31 12 1974),(01 01 1976-31 12 1976)
72 EARL PS	(01 01 1972-31 12 1976)
73 KELSEY PARK	(01 01 1965-28 02 1965),(01 04 1965-31 12 1974)
74 CROSSNESS STW	(01 01 1965-04 01 1971),(07 01 1971-07 01 1971)
	(09 01 1971-31 12 1974),(09 01 1971-31 12 1976)
75 WESTERHAM HILL PS	(01 01 1972-31 12 1976)
76 KESTON	(01 01 1972-29 02 1972),(01 04 1972-31 12 1976)
77 ORPINGTON	(01 01 1963-31 12 1976)

Table 2.2 'Available' PEPR data

Gauge	Periods of available data
1. Bury Farm	April 1972-December 1976
2. Spring Park Farm	July 1972-December 1975
3. Riverside STW	April 1972-December 1975
4. Chigwell STW	March 1973-December 1976
5. Folkstone Road	August 1970-December 1976
6. Waltham Abbey	April 1972-December 1976
7. Muswell Hill	August 1958-November 1961 January-October 1962 March 1963-December 1966 February-October, December 1967
8. Deephams STW	April 1972-December 1976
9. Walthamstow, Lloyd Park	February-April 1974 October 1974-January 1976 June-December 1976
10. Lowhall Farm Depot	January, February 1958 April 1958-January, March 1959 June-August 1959 October 1959-January 1960 March, May-November 1960 January, February 1961 April 1961-March 1962 May, July, September-December 1962 March, April, June-November 1963 March-August, October, November 1964 January, March-July, September 1965 November 1965-September 1970 November 1970-January 1973 August 1973-December 1976
11. Green Lanes	March-December 1963 March-November 1964 March-October 1965 March-December 1966 March-November 1967 February-December 1968 April-November 1969 April-December 1970 April 1971-December 1976
12. Clapton Pond	January-December 1960 March 1961-November 1964 January 1965-July 1974 January 1975-November 1976
13. Auckland Road	November 1971-December 1976

Table 2.2 continued *'Available' PEPR data*

Gauge	Periods of available data
14. Wick Lane	January 1971-April 1973 June 1973-December 1974
15. Lyle Park	October 1973-December 1976
16. Parliament Hill	April 1974-December 1976
17. Regents Park	August 1973-July 1974
18. Western PS	October 1963-December 1967 March-December 1968 March-November 1969 March-December 1970 February 1971-December 1976
19. Kensington Memorial Gns.	April 1974-December 1976
20. Holland Park	July 1972-December 1976
21. Mill Hill	August 1960-December 1976
22. Hampstead	January 1933-December 1940 March 1941-December 1961 March-December 1962 March 1963-April 1965 June 1965-December 1975
23. Golders Hill Park	January-December 1976
24. Stanmore	January 1942-January 1945 March 1945-February 1947 June 1947-December 1971
25. Canons Park	October 1973-December 1976
26. Chandos Rec. Ground	January 1942-May 1945 September 1945-January 1956 March 1956-September 1973
27. Brent Reservoir	March 1948 January 1949-December 1950 July 1953-December 1976
28. Harrow Weald Cem.	January 1972-December 1976
29. Wembley	January 1964-December 1965 February 1966-September 1969
30. Gladstone Park	January 1969-January 1972 April 1972-December 1975

Table 2.2 continued *'Available' PEPR data*

Gauge	Periods of available data
31. Willesdon Works	April 1972-December 1976
32. Stonebridge Park	January 1966-September 1970 September 1971-November 1975
33. Ealing Castlebar	February 1962-December 1965 March 1966-March 1970 July 1970-January 1974 September 1974-September 1976
34. Brentside School	September 1961-December 1962 March 1963-August 1971
35. Sudbury Hill PS	November 1953-October 1956
36. Pinner Cemetery	January 1957-April 1961
37. Northolt Aerodrome	September 1946-December 1973
38. Newton Park Depot	February 1975-December 1976
39. Hares, Wood End Nurseries	October 1928-May 1930 August 1930-March 1937 May 1937-August 1938 October, November 1938 January 1939-January 1941 March 1941-May 1944 June 1961-September 1974
40. Perry Oaks	April 1972-December 1976
41. Hatton Nurseries	January 1973-December 1976
42. Twickenham STW	January 1941-November 1942 January 1943-April 1945
43. Mogden STW	January 1969-December 1976
44. Ruislip	February 1957-January 1963 March 1968-December 1976
45. Uxbridge, Honeycroft NRS	October 1974-December 1976
46. Ashford Common	March 1972-December 1976
47. Hampton	January 1954-December 1974
48. Epsom Water Works	April 1971-September 1974
49. Maldon STW	August 1957-December 1966
50. Hogsmill STW	July 1957-January 1959 March 1959-December 1976

Table 2.2 continued *'Available' PEPR data*

Gauge	Periods of available data
51. Canbury Gardens	February 1948-August 1960 October 1960-December 1961 January 1963-December 1976
52. Kew Observatory	July 1944-December 1974
53. Kew STW	August 1966-December 1976
54. Sutton STW	October 1936-December 1938 January 1940-December 1945 January 1947-December 1974
55. Raynes Park PS	November 1960-December 1961 October, December 1964-December 1976
56. Putney Heath	June 1964-June 1970 August 1970-December 1976
57. Banstead	February 1967-March 1971 November 1971-December 1974
58. How Green Reservoir	May 1972-December 1976
59. Alderstead Heath	October 1962-December 1968
60. Purley Oaks	March 1965-November 1972
61. Beddington Park	October-December 1962 April 1963-December 1964
62. Beddington STW	January 1972-December 1976
63. Carshalton PS	April 1965-September 1970 November 1970-June 1971
64. Morden Hall	January 1960-May 1965 July 1965-September 1966 November 1966-January 1969 March 1969-December 1976
65. London Road	January 1965-February 1972 September 1972-December 1976
66. Gap Road Cemetery	January 1972-December 1976
67. Furzedown Rec. Grd.	April 1974-December 1976
68. King George's Park	April 1974-December 1976
69. Battersea Park	April 1974-December 1976
70. Ruskin Park	April 1974-December 1976

Table 2.2 continued *'Available' PEPR data*

Gauge	Periods of available data
71. Telegraph Hill	April-December 1974 January-December 1976
72. Earl PS	January 1972-December 1976
73. Kelsey Park	April-November 1965 March, May-December 1966 March, May-November 1967 January, February, April-August 1968 October 1968-March 1969 July 1970-December 1974
74. Crossness STW	March, October 1965-September 1970 November 1970-December 1974
75. Westerham Hill PS	April 1972-July 1974 November 1974-December 1976
76. Keston	July 1972-December 1976
77. Orpington	January 1963-November 1971

of the Study. Both the volume of the dataset and its time series form lead to the development of a bespoke database using a host-based file structure rather than the ORACLE proprietary relational database available on the IBM.

The data are held as multiple files, one for each month and station. Unformatted binary files are used to minimise the use of disk space and to speed up accessing of data. The majority of data are held in 16 bit words (the station number is the one exception), having the file size relative to storage based on 32 bit words. The byte values present in the data are stored as byte values: whilst this can reduce the file size by 3-4 % the actual reduction is probably negligible for most files because of disk blocking. Every daily record in a file includes the station number and full date for use in consistency checking within the retrieval routines and to determine the day number of the data.

The full PEPR database for London contains 9972 data files and these occupy 44 Mbytes of disk space.

3. Exploratory data analysis

3.1 INTRODUCTION

A broad view of the extensive PEPR data set can be obtained through the construction of a simple tabulation of the data on a seasonal and annual basis, complemented by a set of simple graphical displays of the data in time series and seasonal histogram form. Such an exploratory data analysis can be used to visualise any obvious features in the data, either in the form of "natural" features such as trends and jumps or "data" features such as missing values.

3.2 SEASONAL DATA TABLES AND GRAPHICAL DISPLAYS

The tabular summaries produced focussed on three quantities

(i) the total rainfall recorded in mm;
(ii) the maximum hourly rainfall in mm; and
(iii) the proportion of days without missing data over the period.

These were calculated for monthly and annual periods over all the years of the PEPR record for a given raingauge. Examples are presented for the Hayes and Hampstead raingauge records in Tables 3.2.1 and 3.2.2 for the periods 1928 to 1974 and 1933 to 1975 respectively. A separate document presents the complete set of tables produced from the 77 raingauges making up the PEPR data set.

Graphical displays of the data contained in these tables are presented in Figures 3.2.1, 3.2.2 and 3.2.3. These present a seasonal histogram of maximum hourly rainfall in each month (calculated over all years) and time series plots of the annual and monthly maximum hourly rainfall. The following general comments can be drawn from an inspection of both tables and figures:-

(i) extreme hourly rainfalls show a tendency to occur in July and August;
(ii) monthly rainfall totals are relatively uniform from month to month throughout the year; and
(iii) based on a visual analysis alone, time series plots of rainfall maxima do not obviously suggest temporal variations which are anything but random.

Observation (i) implies that short duration storms of importance to culvert design and other engineering works have a tendency to occur in summer. Note that the largest storm within the PEPR data set occurred over Hampstead on 14 August 1975 where

Rainfall Totals (mm). Station: 246690

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total	Mths
1933	37.4	16.4	38.3	29.2	50.3	44.1	33.2	16.9	67.8	35.8	25.5	9.3	404.1	12
1934	39.5	2.1	58.6	52.4	15.7	19.4	25.2	56.6	57.1	27.5	52.7	135.2	542.1	12
1935	17.8	60.1	9.4	81.6	29.5	77.4	7.4	52.4	80.9	63.8	98.6	71.8	650.7	12
1936	98.2	36.6	26.9	32.2	10.4	95.0	90.4	8.6	76.9	48.0	76.8	39.0	639.0	12
1937	96.8	107.2	33.1	69.5	74.4	56.4	11.4	65.2	44.5	61.5	39.1	92.2	751.4	12
1938	75.7	10.9	9.3	3.5	47.0	12.9	32.6	53.7	53.1	70.6	78.1	55.9	503.2	12
1939	62.6	19.3	35.7	69.2	37.8	31.8	56.2	62.0	32.9	121.3	116.2	27.5	672.2	12
1940	9.6	28.0	75.3	64.3	35.6	14.9	70.4	2.5	26.3	75.4	167.5	34.3	604.1	12
1941	-999.0	-999.0	61.2	39.3	45.7	64.5	109.8	139.9	15.5	19.7	63.7	51.2	610.5	10
1942	27.0	1.4	47.0	25.5	64.7	6.5	45.4	48.6	26.9	90.7	49.8	57.6	491.2	12
1943	119.5	31.4	8.6	28.9	45.1	7.8	11.6	0.0	13.8	61.1	43.6	34.4	405.9	12
1944	42.2	18.7	3.1	37.6	16.1	45.0	42.3	62.5	66.6	83.7	101.6	33.1	552.3	12
1945	23.4	38.4	16.9	25.6	66.3	49.4	65.5	29.6	33.6	60.5	1.6	49.0	459.7	12
1946	42.1	55.9	26.8	42.9	70.3	83.4	32.2	91.3	102.5	49.3	99.0	41.2	736.8	12
1947	12.3	16.6	54.6	36.9	27.8	67.6	49.7	5.3	35.0	4.7	27.8	44.5	382.7	12
1948	94.8	15.6	18.0	37.1	76.7	46.7	30.2	36.8	28.5	9.6	23.1	51.1	468.0	12
1949	23.7	25.9	21.9	37.2	51.7	15.3	21.6	40.8	8.8	117.9	43.8	41.5	450.0	12
1950	29.2	83.8	14.8	48.9	26.2	12.2	5.0	12.9	22.7	13.3	101.4	21.8	392.2	12
1951	44.8	118.9	87.2	64.3	60.7	28.4	30.6	115.1	79.4	22.4	139.9	39.7	831.3	12
1952	42.2	15.8	57.4	27.3	41.9	33.6	16.4	69.0	84.5	68.8	84.0	56.7	597.5	12
1953	13.5	23.2	7.4	68.4	41.9	45.2	115.3	45.7	47.4	54.8	26.1	18.1	506.8	12
1954	22.6	34.5	48.9	5.5	47.5	57.7	77.4	98.9	47.1	52.0	89.4	45.6	626.9	12
1955	16.2	29.7	23.6	9.9	106.0	41.8	5.3	20.9	46.3	79.3	20.9	53.7	453.5	12
1956	84.6	3.4	3.0	12.0	9.9	68.3	135.6	121.8	62.6	70.6	12.9	62.6	647.2	12
1957	36.3	76.5	31.8	2.5	17.5	1.6	84.0	10.2	60.6	49.6	46.8	50.2	467.6	12
1958	62.1	52.9	28.2	44.6	68.9	118.1	60.5	106.9	112.0	68.3	53.3	78.8	854.5	12
1959	33.3	3.0	55.0	64.2	18.6	32.3	36.5	35.1	2.3	49.4	46.3	91.7	467.7	12
1960	50.3	53.0	46.2	16.4	51.4	41.9	85.3	65.8	127.1	155.6	118.9	60.4	872.3	12
1961	53.9	60.6	4.1	64.7	23.7	37.4	36.0	50.7	66.5	76.5	62.4	46.5	583.0	12
1962	-999.0	-999.0	26.0	56.1	43.8	11.3	102.1	62.2	87.8	47.3	53.9	31.2	521.7	10
1963	-999.0	-999.0	69.5	53.5	47.7	77.0	35.7	81.1	67.4	45.1	116.7	20.5	614.1	10
1964	14.8	23.1	65.9	90.0	86.1	100.4	50.1	34.9	13.8	33.3	42.4	33.9	588.6	12
1965	30.8	14.9	51.4	48.4	-999.0	45.6	106.0	52.1	111.5	10.4	44.2	114.4	629.7	11
1966	7.2	59.5	10.0	95.5	47.3	64.9	16.7	111.4	31.5	91.1	40.6	78.0	653.6	12
1967	41.8	51.8	35.9	64.8	104.2	58.0	40.1	40.8	62.1	100.1	39.9	17.3	656.9	12
1968	40.5	25.0	18.5	42.5	46.1	61.5	7.0	82.2	99.3	66.0	62.4	38.6	589.6	12
1969	57.2	8.5	27.1	10.0	32.0	33.3	73.3	73.8	7.5	8.2	74.0	43.1	448.0	12
1970	39.3	33.1	42.0	74.3	17.2	22.8	49.9	45.3	44.8	9.3	152.3	22.5	552.8	12
1971	60.1	17.6	26.1	39.5	21.8	133.6	29.2	80.8	25.8	57.0	64.9	20.9	577.2	12
1972	61.6	52.8	55.3	42.6	37.5	22.3	21.1	4.6	19.4	18.9	21.8	66.2	424.0	12
1973	1.4	6.4	14.2	52.4	76.6	65.2	22.9	37.3	75.5	29.7	15.6	34.3	431.3	12
1974	58.6	58.6	33.3	12.7	21.7	57.6	31.5	44.9	151.4	79.6	135.2	37.3	722.4	12
1975	85.0	33.7	68.9	44.0	79.2	19.1	15.9	183.7	138.7	16.4	61.5	29.9	776.0	12
Avg.	45.3	35.6	34.8	43.4	46.2	47.2	47.1	57.2	57.3	55.2	66.0	48.4		
Yrs.	40	40	43	43	42	43	43	43	43	43	43	43	43	

Yearly total of monthly averages (mm) 583.7

Average of yearly totals (mm) 577.0

Table 3.2.1a ***Seasonal data table for Hampstead: total rainfall in mm***

Percentage of days where all data are present. Station: 246690

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ov. yr.
1933	0.84	0.61	0.81	0.97	1.00	1.00	0.90	1.00	0.97	0.97	0.80	0.90	0.90
1934	0.97	0.89	0.97	0.97	1.00	1.00	1.00	0.90	1.00	1.00	1.00	0.90	0.97
1935	0.90	1.00	1.00	1.00	1.00	0.97	0.94	1.00	0.93	1.00	0.90	0.94	0.96
1936	0.90	0.90	0.97	0.97	0.97	1.00	0.94	0.97	0.93	1.00	1.00	0.81	0.95
1937	0.94	0.93	0.81	1.00	1.00	0.97	0.97	1.00	1.00	0.97	1.00	0.90	0.96
1938	1.00	0.86	1.00	0.97	1.00	1.00	0.94	1.00	1.00	0.97	0.97	0.74	0.95
1939	0.77	0.96	0.94	0.90	1.00	1.00	1.00	0.97	0.97	0.94	0.97	0.87	0.94
1940	0.71	0.69	0.97	0.97	1.00	0.97	1.00	1.00	1.00	0.97	1.00	0.97	0.94
1941	0.00	0.00	0.90	0.97	1.00	0.97	0.97	0.97	1.00	1.00	1.00	0.87	0.81
1942	0.74	0.86	0.97	1.00	1.00	0.97	0.97	1.00	0.93	0.97	0.97	0.94	0.94
1943	1.00	0.50	1.00	1.00	1.00	0.43	0.58	0.16	0.40	1.00	1.00	1.00	0.76
1944	0.97	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.94	1.00	0.97	0.99
1945	0.55	1.00	0.97	1.00	0.97	1.00	0.94	1.00	0.97	1.00	0.90	0.77	0.92
1946	1.00	0.93	0.97	1.00	0.94	0.97	0.94	0.94	0.97	1.00	0.93	0.90	0.96
1947	0.58	0.68	0.68	0.90	1.00	0.93	1.00	1.00	1.00	1.00	0.93	0.84	0.88
1948	0.94	0.83	0.97	0.97	0.97	0.90	1.00	0.87	0.93	0.77	0.83	0.90	0.91
1949	1.00	1.00	0.97	0.93	0.97	1.00	0.90	0.94	1.00	1.00	0.80	1.00	0.96
1950	0.90	0.96	0.94	0.90	0.90	0.63	0.32	0.71	0.50	1.00	0.97	0.74	0.79
1951	0.90	0.96	1.00	0.97	1.00	1.00	1.00	1.00	1.00	0.97	0.97	0.97	0.98
1952	0.94	0.90	0.90	0.97	0.97	1.00	1.00	1.00	1.00	1.00	0.97	0.90	0.96
1953	0.97	0.86	1.00	1.00	1.00	1.00	1.00	0.97	1.00	0.90	1.00	1.00	0.98
1954	0.94	0.82	0.87	0.97	1.00	0.87	1.00	1.00	0.97	1.00	1.00	0.97	0.95
1955	0.61	0.71	0.90	0.63	0.97	0.93	0.94	0.94	1.00	0.97	1.00	0.97	0.88
1956	0.87	0.79	0.77	0.90	0.97	0.97	1.00	1.00	0.97	1.00	1.00	0.87	0.93
1957	0.97	0.96	1.00	0.90	0.77	0.87	0.94	0.77	0.90	0.97	0.97	1.00	0.92
1958	0.90	0.93	0.90	1.00	0.97	1.00	1.00	1.00	1.00	1.00	0.97	0.97	0.97
1959	0.77	0.96	1.00	1.00	1.00	0.97	1.00	0.97	1.00	0.97	0.97	1.00	0.97
1960	0.94	0.93	1.00	0.97	1.00	1.00	0.97	1.00	1.00	1.00	0.97	0.94	0.98
1961	0.97	1.00	1.00	1.00	1.00	1.00	1.00	0.94	1.00	1.00	1.00	0.35	0.94
1962	0.00	0.00	0.39	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.74	0.76
1963	0.00	0.00	1.00	0.97	1.00	1.00	1.00	1.00	1.00	1.00	0.97	1.00	0.83
1964	0.94	0.97	0.97	1.00	1.00	1.00	1.00	1.00	1.00	0.74	0.70	1.00	0.94
1965	0.77	0.96	0.94	0.97	0.00	1.00	0.94	1.00	0.97	1.00	0.90	1.00	0.87
1966	0.74	0.75	1.00	1.00	1.00	1.00	0.74	1.00	1.00	0.97	1.00	0.97	0.93
1967	1.00	0.96	1.00	1.00	1.00	1.00	1.00	0.97	1.00	0.97	1.00	0.71	0.97
1968	0.87	1.00	0.90	0.83	1.00	1.00	0.81	0.97	0.97	1.00	1.00	0.84	0.93
1969	0.94	0.86	0.90	0.83	0.81	1.00	1.00	0.97	1.00	1.00	0.90	0.94	0.93
1970	0.74	0.82	0.90	1.00	1.00	0.97	0.90	0.87	0.93	0.90	0.90	0.77	0.89
1971	0.68	1.00	0.94	1.00	0.87	1.00	1.00	0.97	1.00	0.94	0.93	0.97	0.94
1972	1.00	1.00	1.00	0.93	1.00	1.00	0.97	0.97	0.97	1.00	0.80	0.90	0.96
1973	0.74	0.93	0.97	1.00	1.00	1.00	0.97	0.97	1.00	1.00	0.97	0.94	0.96
1974	1.00	0.96	1.00	1.00	1.00	1.00	1.00	0.90	1.00	1.00	0.93	0.97	0.98
1975	0.94	1.00	0.97	0.97	1.00	1.00	0.97	0.97	0.97	1.00	1.00	0.97	0.98
over all yrs.	0.81	0.83	0.93	0.96	0.95	0.96	0.94	0.94	0.96	0.97	0.95	0.90	

Table 3.2.1b ***Seasonal data table for Hampstead: proportion of days without missing data***

Maximum Hourly Totals (mm). Station: 246690

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ov. yr.
1933	7.0	2.5	2.4	5.4	4.3	6.4	6.5	1.6	7.0	2.8	4.9	1.7	7.0
1934	1.9	0.4	3.9	7.5	2.9	2.5	7.6	4.9	9.1	2.0	2.8	3.6	9.1
1935	5.0	2.3	1.4	3.5	3.8	6.3	2.6	7.1	6.2	4.5	4.1	2.8	7.1
1936	10.0	2.7	1.8	2.4	3.5	12.2	13.1	1.2	6.7	5.3	3.8	3.7	13.1
1937	4.5	3.6	3.2	3.7	7.8	18.6	1.8	20.6	2.6	5.5	6.6	5.2	20.6
1938	3.6	2.2	1.1	1.4	3.5	1.9	5.6	6.5	7.4	4.6	6.6	3.8	7.4
1939	4.1	2.3	5.2	4.4	2.8	3.7	6.6	7.1	12.8	6.6	5.1	2.6	12.8
1940	4.4	2.8	3.6	14.6	4.3	5.7	5.1	1.6	3.6	8.6	5.9	3.0	14.6
1941	-999.9	-999.9	2.7	4.8	2.5	6.9	15.3	9.1	5.4	2.5	5.9	7.9	15.3
1942	3.5	0.2	2.6	2.2	4.8	2.3	4.9	4.9	2.0	8.8	5.3	4.8	8.8
1943	4.2	4.0	1.7	1.8	3.1	1.5	8.6	0.0	3.0	5.3	4.0	3.6	8.6
1944	3.7	2.1	0.9	4.9	4.9	4.4	7.2	10.9	5.5	6.6	6.3	2.8	10.9
1945	3.4	2.2	2.1	2.9	9.2	3.6	18.5	2.4	2.0	5.6	0.7	5.7	18.5
1946	3.8	3.9	2.0	4.7	6.7	4.2	3.8	8.9	11.4	7.3	6.6	2.8	11.4
1947	2.6	3.4	3.2	3.8	4.0	15.3	6.4	1.6	10.8	2.2	3.2	4.5	15.3
1948	6.8	1.8	3.8	3.6	15.5	8.1	2.3	7.9	4.3	1.3	3.7	4.5	15.5
1949	2.9	2.4	1.6	2.9	6.2	1.8	4.5	7.3	1.2	6.9	3.7	5.1	7.3
1950	3.1	3.4	1.9	3.0	2.7	2.0	0.9	3.3	3.8	2.6	3.6	5.5	5.5
1951	2.2	3.1	5.9	2.8	4.1	4.1	4.6	9.5	6.9	3.3	7.2	1.8	9.5
1952	5.2	1.3	3.5	3.0	6.1	3.9	2.9	14.3	6.2	4.7	3.9	3.1	14.3
1953	4.0	1.4	1.9	4.1	5.2	4.2	11.6	5.7	5.1	8.4	3.6	2.3	11.6
1954	8.3	2.4	2.9	1.3	3.1	7.5	6.3	20.9	4.8	5.1	3.7	8.0	20.9
1955	4.3	3.5	2.8	1.2	5.9	6.1	1.6	4.5	5.0	6.3	2.0	2.1	6.3
1956	4.2	0.4	0.8	1.7	3.3	7.2	22.0	8.6	7.0	14.4	3.4	3.8	22.0
1957	3.6	4.0	3.6	0.8	2.0	1.2	6.8	2.1	3.7	8.1	7.2	2.6	8.1
1958	5.9	3.7	1.9	6.4	7.7	5.8	6.1	17.8	8.1	4.8	3.3	4.5	17.8
1959	3.3	1.0	5.2	3.6	2.9	7.8	9.0	5.5	0.8	6.1	3.8	4.6	9.0
1960	4.3	3.6	4.2	1.1	3.5	3.8	6.4	8.3	15.7	6.3	6.5	4.3	15.7
1961	3.6	2.7	0.6	2.4	6.2	4.3	8.1	9.6	7.6	5.6	3.6	3.5	9.6
1962	-999.9	-999.9	2.8	3.3	6.0	1.6	8.5	5.7	6.1	9.1	3.1	2.7	9.1
1963	-999.9	-999.9	2.1	2.1	4.0	10.3	4.7	3.8	8.8	4.5	5.3	1.9	10.3
1964	2.3	3.0	4.2	9.4	20.4	8.3	10.4	2.9	1.6	3.8	4.1	2.4	20.4
1965	2.6	1.7	4.5	4.0	-999.9	3.5	36.9	3.1	5.9	2.7	4.0	3.3	36.9
1966	2.5	6.4	1.1	3.5	2.9	8.1	5.4	11.0	3.4	9.4	4.2	3.1	11.0
1967	2.1	5.3	3.0	4.0	5.3	10.6	8.7	3.5	5.0	6.0	5.5	2.4	10.6
1968	1.9	4.2	3.0	7.6	3.7	5.9	1.8	8.7	5.9	7.0	17.2	7.0	17.2
1969	3.9	2.2	2.1	2.9	3.3	2.5	4.4	11.2	1.0	1.8	7.0	3.8	11.2
1970	1.9	2.2	6.4	4.8	2.5	3.4	6.3	10.6	6.5	1.9	5.4	2.3	10.6
1971	4.3	2.4	2.5	2.4	2.5	5.7	4.3	12.6	5.3	4.2	5.3	4.5	12.6
1972	2.6	3.2	5.3	4.0	2.7	1.6	2.8	0.8	7.0	4.5	2.0	9.0	9.0
1973	0.5	0.8	1.7	2.7	7.1	8.0	5.3	4.9	5.7	2.7	2.3	3.7	8.0
1974	4.2	5.2	4.3	2.9	2.7	4.4	3.3	4.1	5.1	4.6	6.8	5.4	6.8
1975	4.7	3.3	3.8	2.7	8.2	2.6	4.4	72.8	11.2	2.7	6.5	2.8	72.8
over all yrs.	10.0	6.4	6.4	14.6	20.4	18.6	36.9	72.8	15.7	14.4	17.2	9.0	72.8

Table 3.2.1c ***Seasonal data table for Hampstead: maximum hourly rainfall in mm***

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total	Mths
1928	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	89.7	23.6	24.9	138.2	3
1929	25.0	2.4	0.3	18.0	21.1	23.2	15.5	29.8	7.6	48.4	124.9	96.6	413.0	12
1930	55.3	12.5	29.0	42.1	60.0	-999.0	-999.0	34.8	63.8	24.1	85.0	38.8	445.3	10
1931	24.4	34.3	2.9	74.4	55.5	41.6	68.4	127.4	40.5	16.5	60.9	14.7	561.6	12
1932	43.6	1.7	8.8	31.9	81.3	20.6	39.6	38.1	37.9	81.1	26.1	9.6	420.4	12
1933	31.5	36.9	48.6	13.4	38.3	42.5	35.7	14.2	17.8	32.3	26.2	10.0	347.3	12
1934	29.4	2.7	56.0	53.1	12.7	0.0	30.0	68.8	35.7	31.2	44.6	82.1	446.3	12
1935	19.2	48.9	7.1	63.5	20.5	77.8	15.8	48.3	82.3	57.9	71.9	57.6	570.9	12
1936	95.2	41.6	24.9	31.1	13.5	75.4	53.7	7.8	58.1	33.2	70.3	30.3	535.0	12
1937	65.4	78.7	62.0	-999.0	59.3	44.0	24.2	10.5	54.1	62.2	32.5	76.8	569.7	11
1938	52.3	8.7	8.3	4.1	41.1	12.2	23.6	64.9	-999.0	45.9	68.6	-999.0	329.6	10
1939	97.6	20.6	28.8	62.5	32.0	30.5	47.2	79.5	18.8	115.7	96.4	19.5	649.0	12
1940	56.5	31.9	66.8	38.2	31.7	27.4	58.6	0.8	24.8	54.2	94.0	29.0	513.9	12
1941	13.7	-999.0	66.5	37.7	44.8	45.8	103.0	120.4	12.2	19.2	65.4	37.2	565.8	11
1942	27.1	4.7	28.7	34.3	73.2	8.2	37.3	55.4	16.0	86.6	20.0	56.0	447.4	12
1943	100.4	32.8	9.8	18.3	44.8	16.0	47.8	32.0	42.5	67.3	32.3	29.8	473.7	12
1944	41.3	20.3	3.4	35.5	29.4	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	129.9	5
1945	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	0
1946	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	0
1947	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	0
1948	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	0
1949	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	0
1950	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	0
1951	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	0
1952	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	0
1953	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	0
1954	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	0
1955	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	0
1956	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	0
1957	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	0
1958	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	0
1959	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	0
1960	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	0
1961	-999.0	-999.0	-999.0	-999.0	-999.0	0.6	19.9	66.0	71.1	66.6	52.4	68.2	344.7	7
1962	81.0	11.6	16.4	49.3	33.0	6.9	88.1	30.7	90.2	37.6	51.0	39.8	535.7	12
1963	1.8	2.2	73.3	51.2	41.5	51.2	28.7	63.0	50.7	28.0	124.7	14.5	531.0	12
1964	13.0	6.7	67.3	74.4	44.8	105.1	30.1	24.0	11.1	20.5	31.2	23.8	451.9	12
1965	39.1	7.6	7.1	41.0	49.1	39.4	43.4	44.8	104.2	18.5	46.3	76.7	517.0	12
1966	29.7	66.5	11.4	67.4	48.3	65.5	70.6	76.8	30.8	86.1	14.6	47.2	615.0	12
1967	23.1	53.9	42.1	47.0	102.6	52.6	47.6	43.0	53.3	112.0	22.8	25.1	625.2	12
1968	36.4	21.6	22.8	52.2	68.3	42.5	70.1	65.9	149.9	55.8	44.2	37.7	667.6	12
1969	23.4	6.6	48.3	18.1	34.1	23.6	29.0	28.7	3.3	2.8	70.2	42.3	330.3	12
1970	22.1	36.9	27.8	57.9	18.8	19.6	55.9	27.4	53.0	9.0	88.4	28.4	445.2	12
1971	56.7	15.3	41.3	50.0	72.3	82.5	14.1	56.5	8.9	36.4	65.4	23.5	522.7	12
1972	41.2	36.6	51.8	39.1	33.8	19.7	17.2	17.0	31.4	17.7	58.7	47.0	411.3	12
1973	17.4	10.5	9.8	30.3	66.3	32.3	15.9	36.9	72.2	26.4	29.9	49.0	396.7	12
1974	58.7	61.7	29.5	15.8	33.8	51.5	29.6	52.6	78.2	-999.0	-999.0	-999.0	411.4	9
Avg.	42.1	25.6	31.1	41.1	45.0	37.8	41.4	47.1	47.2	47.7	56.6	40.6		
Yrs.	29	28	29	28	29	28	28	29	28	29	29	28	31	

Yearly total of monthly averages (mm) 503.3

Average of yearly totals (mm) 463.3

Table 3.2.2a ***Seasonal data table for Hayes: total rainfall in mm***

Percentage of days where all data are present. Station: 247449

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ov. yr.
1928	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.90	0.83	0.97	0.23
1929	1.00	0.96	1.00	0.93	0.97	1.00	0.90	0.97	1.00	0.90	1.00	0.81	0.95
1930	0.94	1.00	0.94	0.97	0.97	0.00	0.00	0.52	0.97	1.00	0.97	0.97	0.77
1931	0.97	1.00	1.00	0.97	1.00	1.00	0.94	1.00	0.93	1.00	1.00	0.97	0.98
1932	0.94	0.97	0.84	0.87	0.90	0.73	0.90	0.97	0.93	0.77	0.93	1.00	0.90
1933	0.90	0.96	0.90	0.93	1.00	1.00	1.00	0.97	0.73	1.00	0.87	1.00	0.94
1934	1.00	0.93	1.00	1.00	0.94	0.57	1.00	0.94	1.00	0.97	1.00	0.77	0.93
1935	1.00	1.00	1.00	1.00	0.97	0.97	1.00	0.97	0.97	0.97	0.93	0.97	0.98
1936	1.00	1.00	1.00	0.97	1.00	0.97	1.00	1.00	0.97	1.00	0.83	0.90	0.97
1937	0.97	0.75	1.00	0.00	0.90	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.89
1938	1.00	1.00	0.58	0.40	0.74	0.77	0.81	0.87	0.00	0.45	0.60	0.00	0.60
1939	0.94	0.93	0.61	1.00	0.97	0.97	0.84	0.97	0.93	0.81	0.80	0.84	0.88
1940	0.94	0.97	0.94	0.93	0.97	0.90	0.90	1.00	0.90	0.81	0.43	0.90	0.88
1941	0.55	0.00	0.87	1.00	1.00	0.97	0.94	0.97	1.00	0.97	0.97	0.97	0.85
1942	0.90	0.93	0.87	1.00	1.00	1.00	1.00	0.97	0.93	1.00	0.97	0.97	0.96
1943	0.94	0.96	1.00	0.97	0.97	0.80	1.00	0.97	1.00	1.00	1.00	1.00	0.97
1944	1.00	1.00	1.00	0.97	0.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.40
1945	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1946	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1947	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1948	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1949	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1950	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1951	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1952	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1953	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1954	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1955	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1956	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1957	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1958	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1959	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1960	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1961	0.00	0.00	0.00	0.00	0.00	0.50	0.94	1.00	1.00	1.00	1.00	0.97	0.54
1962	0.94	1.00	0.87	1.00	0.97	1.00	0.97	0.94	1.00	1.00	1.00	0.90	0.96
1963	0.45	0.75	0.90	0.97	1.00	1.00	1.00	1.00	1.00	0.90	1.00	0.90	0.91
1964	0.90	0.86	0.94	0.97	1.00	1.00	1.00	1.00	1.00	0.97	0.97	0.90	0.96
1965	0.87	0.96	0.74	0.97	1.00	0.93	0.87	0.94	0.97	1.00	0.83	0.90	0.92
1966	0.77	0.93	0.97	0.83	1.00	0.97	0.97	0.94	1.00	0.90	0.87	0.87	0.92
1967	0.68	1.00	1.00	0.97	0.90	1.00	0.97	0.97	0.83	0.97	0.93	0.77	0.92
1968	0.87	0.97	1.00	0.97	1.00	0.93	1.00	1.00	1.00	1.00	1.00	0.61	0.95
1969	0.74	0.86	0.97	0.97	0.84	1.00	0.94	0.90	0.97	1.00	1.00	0.90	0.92
1970	0.52	0.96	0.94	1.00	0.97	1.00	1.00	0.97	0.97	1.00	0.80	0.87	0.92
1971	0.84	1.00	1.00	1.00	0.97	0.97	1.00	0.97	1.00	0.90	0.97	1.00	0.97
1972	0.87	0.93	0.97	0.97	0.97	0.97	0.94	1.00	1.00	1.00	0.97	0.90	0.96
1973	1.00	0.89	1.00	0.93	1.00	0.97	0.55	1.00	1.00	0.97	0.97	0.94	0.93
1974	0.97	1.00	0.94	1.00	0.97	0.93	1.00	0.90	0.50	0.00	0.00	0.00	0.68
over all yrs.	0.54	0.56	0.57	0.56	0.59	0.55	0.56	0.59	0.56	0.58	0.56	0.54	

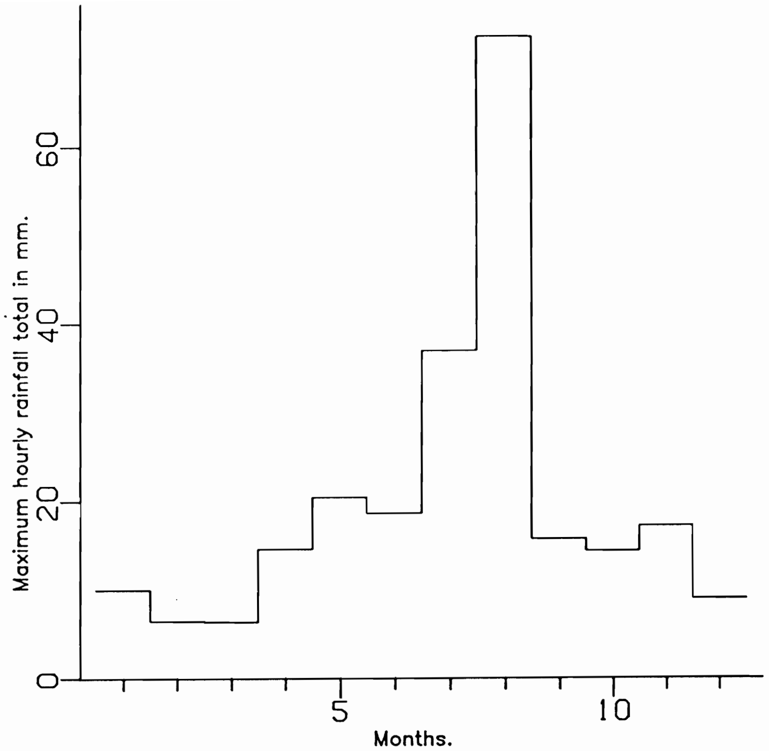
Table 3.2.2b ***Seasonal data table for Hayes: proportion of days without missing data***

Maximum Hourly Totals (mm). Station: 247449

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ov. yr.
1928	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	10.0	3.2	2.1	10.0
1929	2.7	0.8	0.1	1.5	1.7	3.6	2.0	2.2	4.4	5.2	6.6	10.1	10.1
1930	3.6	1.7	3.2	4.4	3.5	-999.9	-999.9	13.1	5.0	2.4	4.8	3.8	13.1
1931	1.6	2.6	0.5	3.7	7.0	5.6	5.1	7.0	4.6	2.8	4.1	1.6	7.0
1932	4.4	0.9	1.0	2.1	10.4	7.5	7.5	18.5	5.0	7.3	2.5	1.1	18.5
1933	6.4	4.9	4.3	2.2	5.2	6.8	11.3	2.3	2.5	4.1	3.1	2.1	11.3
1934	1.8	0.7	4.3	5.2	1.9	0.0	5.0	8.9	4.3	2.7	4.4	8.9	8.9
1935	2.7	2.9	1.6	2.6	2.1	5.8	10.9	6.7	8.6	6.7	7.6	3.2	10.9
1936	8.0	3.1	1.7	1.9	3.1	5.4	3.4	0.8	5.4	4.9	3.6	2.6	8.0
1937	3.0	3.2	4.4	-999.9	6.3	6.2	10.8	2.5	7.4	5.4	4.6	5.2	10.8
1938	2.4	1.6	1.4	0.7	4.7	1.9	1.8	7.1	-999.9	3.2	7.1	-999.9	7.1
1939	5.2	3.4	3.2	4.2	2.7	2.1	7.3	10.6	6.1	5.4	5.1	4.1	10.6
1940	7.9	2.9	3.5	4.7	4.3	9.2	5.6	0.7	2.6	5.7	4.0	3.3	9.2
1941	3.2	-999.9	3.8	4.3	3.1	5.1	38.8	10.3	3.3	2.7	4.2	5.2	38.8
1942	4.9	1.1	4.4	3.3	9.5	3.7	4.8	11.1	1.3	6.0	3.1	7.3	11.1
1943	4.4	4.3	1.9	2.5	4.4	2.2	6.4	5.8	8.2	5.2	2.1	3.7	8.2
1944	5.0	3.2	1.6	4.6	11.2	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	11.2
1945	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9
1946	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9
1947	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9
1948	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9
1949	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9
1950	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9
1951	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9
1952	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9
1953	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9
1954	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9
1955	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9
1956	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9
1957	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9
1958	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9
1959	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9
1960	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9	-999.9
1961	-999.9	-999.9	-999.9	-999.9	-999.9	0.0	3.8	21.4	7.9	5.4	4.7	4.0	21.4
1962	5.9	1.6	1.3	3.7	3.9	1.5	12.5	3.7	7.5	4.2	3.8	3.1	12.5
1963	0.1	0.3	3.2	2.8	3.6	8.1	4.7	3.6	3.3	4.2	6.1	1.9	8.1
1964	1.7	1.0	3.7	6.1	6.3	8.5	4.6	4.8	1.4	2.4	2.6	1.9	8.5
1965	3.6	0.9	1.0	2.3	4.6	8.5	6.0	3.9	11.4	4.0	3.3	3.1	11.4
1966	2.9	2.7	1.0	3.2	4.2	9.1	8.4	9.0	2.8	9.0	3.4	2.5	9.1
1967	1.9	3.9	3.6	3.8	9.0	14.2	8.1	4.9	8.2	7.1	2.0	3.6	14.2
1968	2.0	2.6	2.8	9.5	5.1	6.0	5.7	6.7	9.6	6.2	4.3	6.4	9.6
1969	2.0	1.7	2.9	2.0	3.5	2.1	3.2	3.4	0.7	0.9	5.5	3.0	5.5
1970	2.6	1.8	3.0	2.8	2.3	3.1	5.7	3.6	5.6	1.6	4.9	2.8	5.7
1971	3.3	1.6	2.4	4.3	6.6	4.7	2.1	11.1	4.5	4.5	5.9	5.0	11.1
1972	2.3	4.1	3.8	3.8	3.4	2.0	3.1	4.1	3.7	2.6	5.1	4.0	5.1
1973	1.5	2.6	1.2	2.5	5.4	12.3	4.9	9.0	10.6	3.1	3.9	3.4	12.3
1974	5.9	2.7	3.5	5.1	4.5	6.0	2.7	12.4	8.5	-999.9	-999.9	-999.9	12.4
over all yrs.	8.0	4.9	4.4	9.5	11.2	14.2	38.8	21.4	11.4	10.0	7.6	10.1	38.8

Table 3.2.2c ***Seasonal data table for Hayes: maximum hourly rainfall in mm***

Hampstead



Hayes

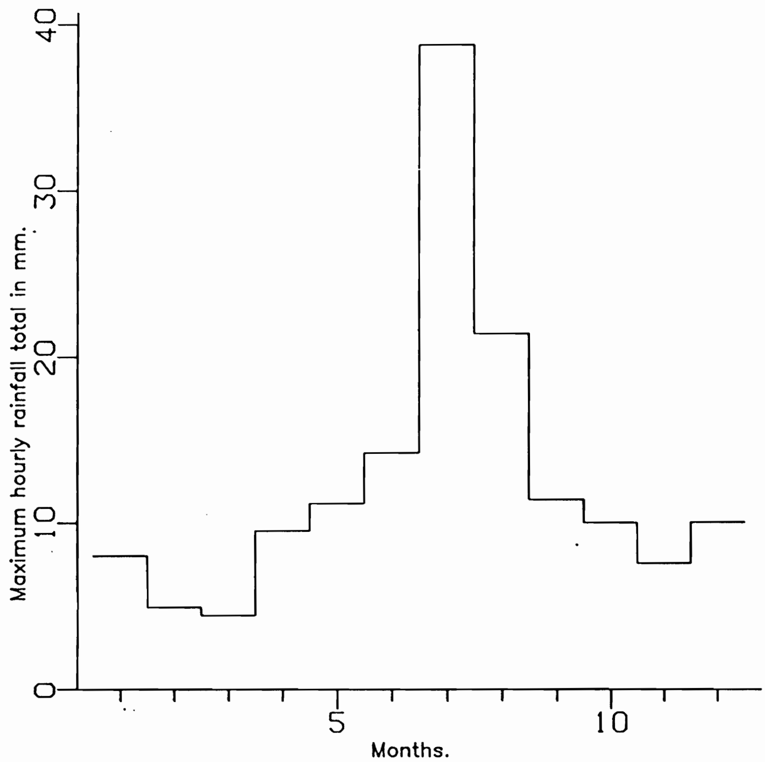
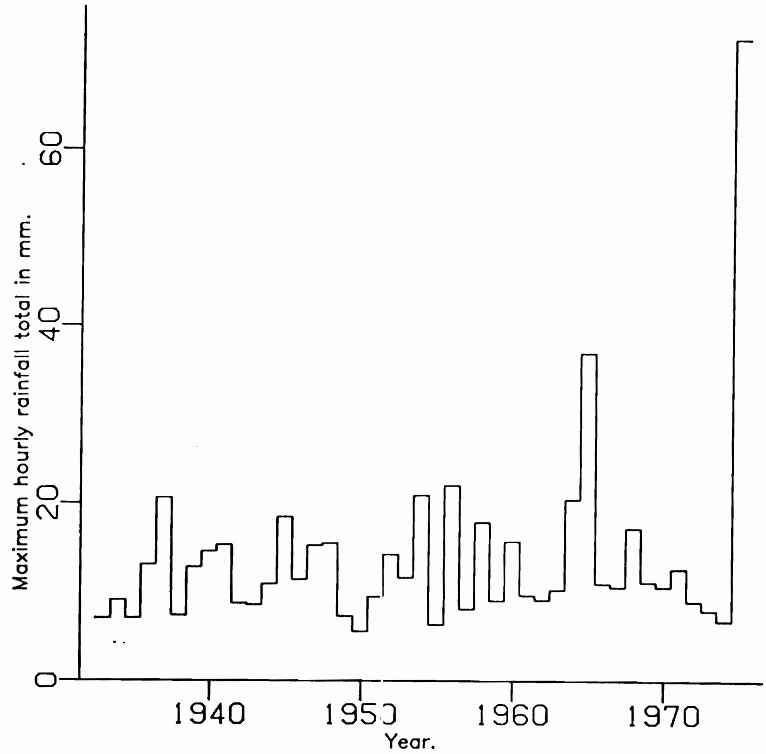


Figure 3.2.1 *Maximum hourly rainfall in each month of the year calculated over all years*

Hampstead: 1933-1975



Hayes: 1928-1974

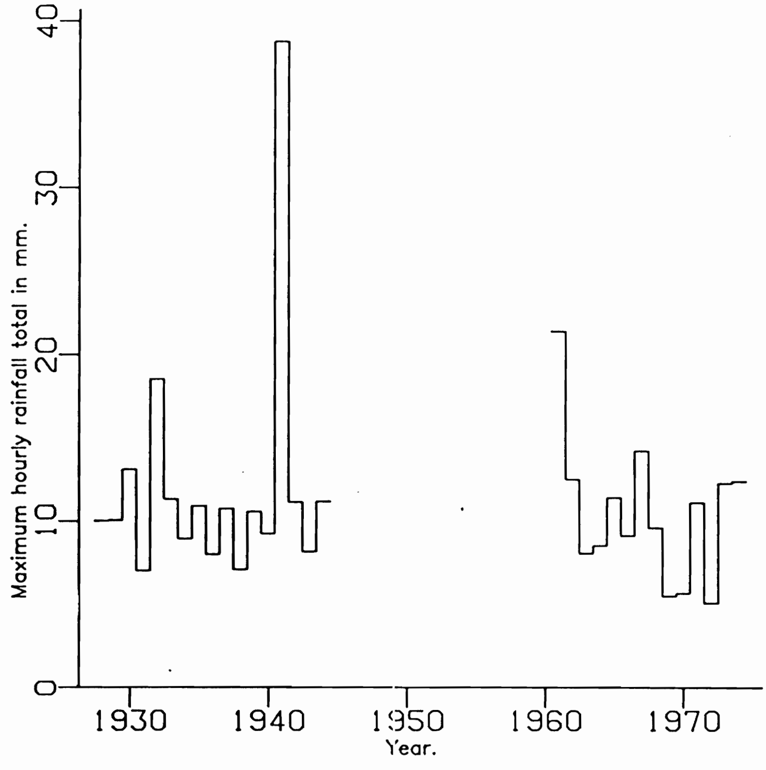
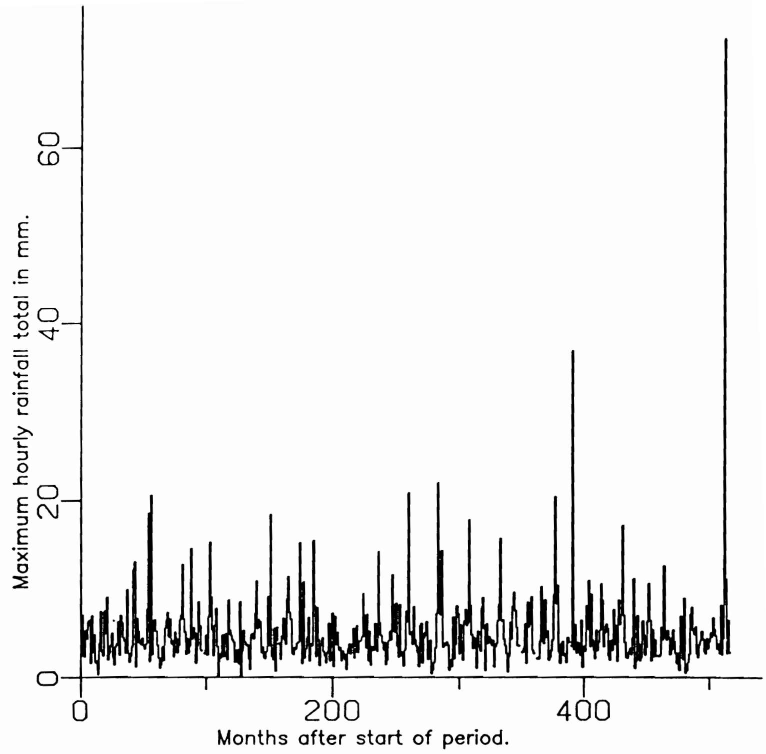


Figure 3.2.2 ***Time series of maximum hourly rainfall in each year of record***

Hampstead: 1933-1975



Hayes: 1928-1974

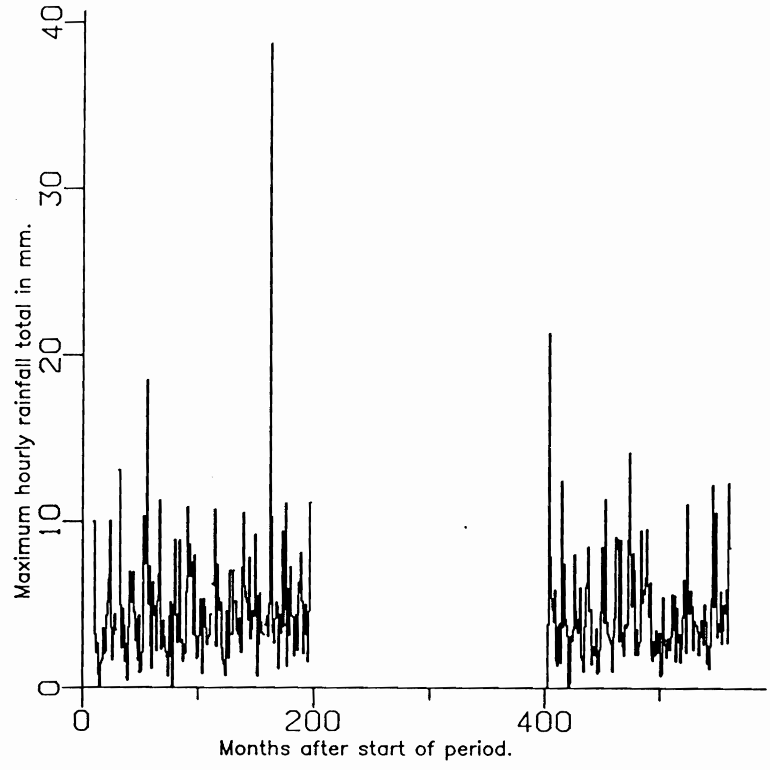


Figure 3.2.3 *Time series of maximum hourly rainfall in each month of record*

72.8 mm fell in one hour. Section 4 pursues the idea that additional insights into rainfall variability may be gained through detailed analysis of specific extreme storm events affecting the London metropolitan area.

3.3 Missing data displays

The prevalence of missing data exposed by the seasonal data tables prompted the development of an additional exploratory data analysis tool. Missing data can be particularly important for analyses using the PEPR data set to derive return period values. Particularly important was the need to assess whether data were more likely to be missing at several sites at the same time which, if the case, might not distort the spatial pattern of return period values as much as the degree of missing data might imply.

In order to investigate the propensity for data to be missing at many sites for a given time a graphical form of display was devised which revealed the information in compact form. This display was constructed by plotting a line between two data values for a given raingauge at a constant elevation on the ordinate axis, the line being omitted when either were missing. This yields a straight horizontal line with gaps where data are missing. By repeating this for each raingauge record, and selecting a different elevation on the ordinate axis for each, then a set of time-synchronised lines results. The display serves to visualise the occurrence of missing values and their joint occurrence in time.

A daily data interval has been used to analyse the complete data record and an hourly one to display a year at a time. In the case of the daily display, the plot has been augmented by the addition of ticks on the day of each year having the maximum hourly total for that year. For the hourly display over one year, ticks are used to indicate the hour of the maximum hourly rainfall for each month. Again this provides an indication of the joint occurrence of these extremes across sites.

Examples of these two forms of display are shown in Figures 3.3.1 and 3.3.2. Figure 3.3.1 shows the missing hourly periods in 1972 for 57 raingauges chosen to have at least 5 years worth of data, as defined using Table 2.1. Figures 3.3.2 shows the missing daily periods between 1928 and 1976 for the same set of gauges. It can be seen that most of the data have been recorded within the last twenty years of the time span. This daily display is useful in assessing missing data on larger time spans, whilst the hourly display of Figure 3.3.1 provides information on the detail of the missing data.

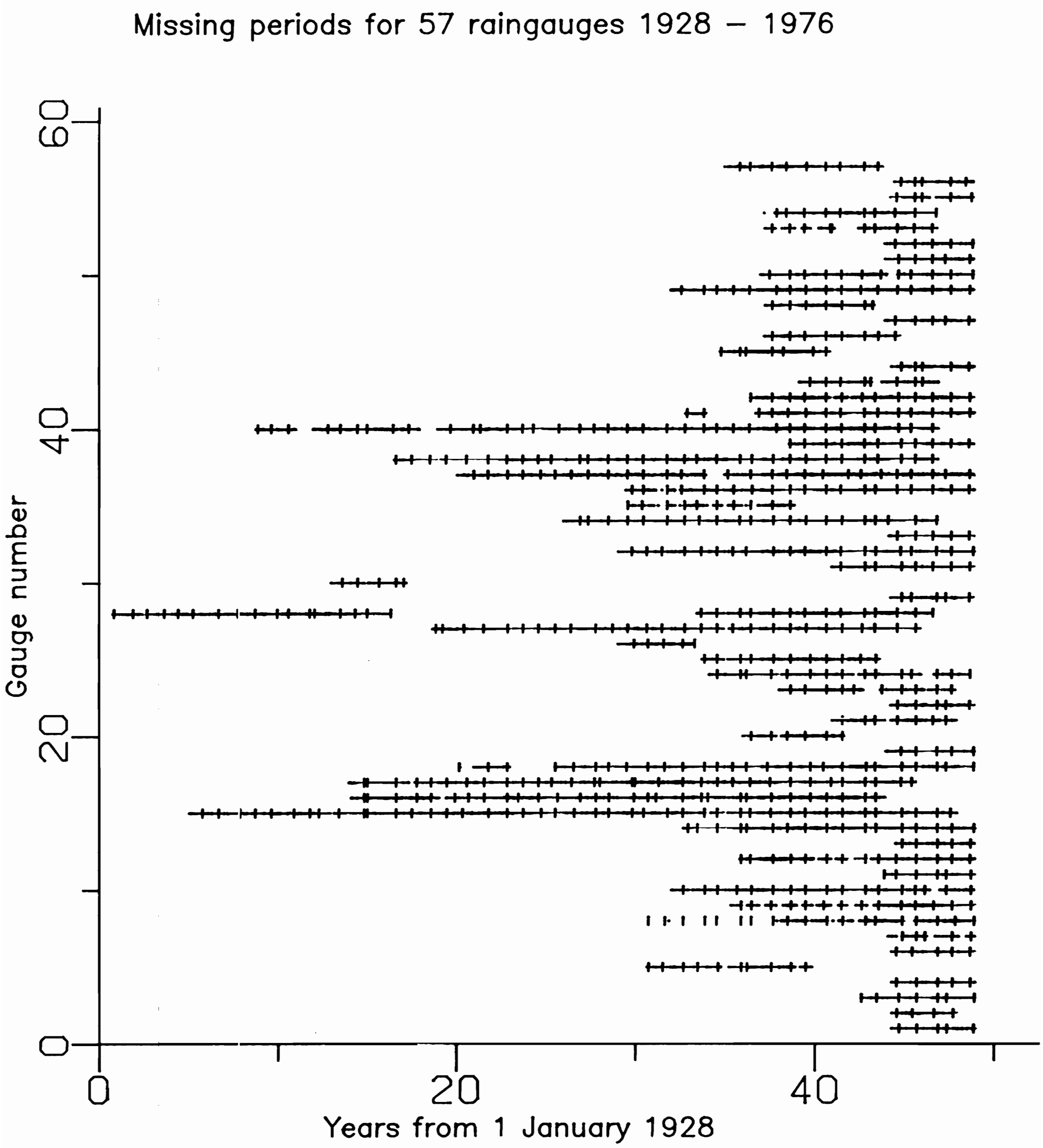


Figure 3.3.1 ***Daily data display for missing value analysis across 57 raingauge sites: 1928-1976***

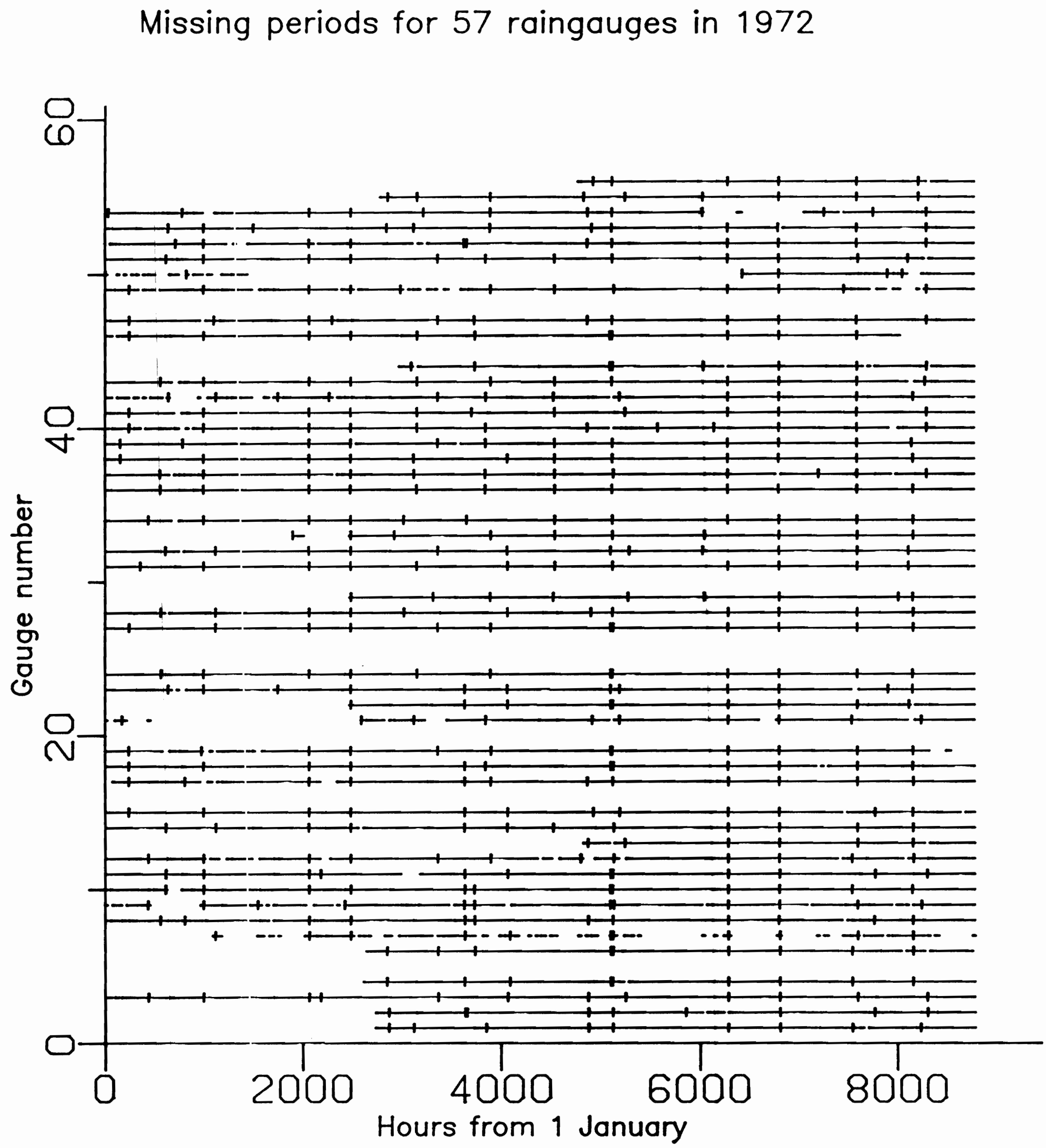


Figure 3.3.2 ***Hourly data display for missing value analysis across 57 raingauge sites: 1972***

4. Mapping of notable storm events

4.1 INTRODUCTION

A major objective of the Study was to investigate whether preferential areas for intense storm activity exists over the London conurbation. Mapping of the isohyets for notable storm events provides an obvious and simple means of searching for such preferential areas. This Section develops an automatic method for constructing isohyetal maps and applies it to selected storms over the London area. This is complemented by an analysis of the storm profiles for the same set of storms.

The NRA Thames Region have made an inventory of major storms, ranking storms roughly in order of the largest recorded rainfall for each event. This inventory was used to select 15 storms for analysis: these are tabulated in Table 4.1 below.

Table 4.1 Notable storm events over London selected for isohyetal mapping

Date	Maximum rainfall in mm	Raingauge with maximum	Number of gauges
6 August 1952	73.7	Stanmore	7
7 June 1963	54.6	Brent Reservoir	21
6 July 1969	51.3	Banstead	26
24 May 1971	50.9	Brent Reservoir	24
4 August 1971	51.5	Western PS	26
19 June 1973	59.7	Epsom Water Works	40
6 July 1973	35.6	Green Lanes	47
1 August 1973	42.3	Putney Heath	32
20 September 1973	73.0	Westerham Hill PS	42
27 June 1974	15.6	Kelsey Park	48
4 September 1974	35.9	Keston	50
17 November 1974	30.9	Uxbridge, Honeycroft NRS	44
21 November 1974	41.2	Parliament Hill	40
14 August 1975	170.8	Hampstead	41
13 September 1975	58.5	Furzedown	37

To serve as the basis of mapping, the daily total for these notable events were extracted from the PEPR archive for each gauge recording rainfall. Table 4.1 indicates the number of gauges from which data are available for each of the 15 events; on average there are 35.

4.2 INTERPOLATION FOR MAPPING

To convert the point rainfall totals to a spatial rainfall field for subsequent mapping requires a method of interpolation. The multiquadratic surface fitting technique developed for the London Weather Radar Local Calibration Study has been employed. In the present application the aim is to depict the actual rainfall field, whereas the Calibration Study required a reasonably smooth surface which was conservative in modifying the radar-derived rainfall intensities towards the raingauge measured intensities. However, the same Study developed a surface fitting method suitable for inferring the rainfall from a network of raingauges, in the absence of radar data, and it is this method that is adopted here for interpolation.

Specifically the approach defines the multiquadatic surface as

$$z_i = a_0 + a_1 d_{i1} + a_2 d_{i2} + \ldots + a_N d_{iN} \qquad i = 1,2,\ldots,N \qquad (4.1)$$

where z_i is a log-transform of the daily storm total in mm for gauge i, d_{ij} is the exponential form of the Euclidean distance, $\exp(-D_{ij}/\ell)$, where D_{ij} is the distance between sites i and j and ℓ is the scaling length, here set to 20 km, $\{a_j, 1=0,1,2,\ldots,N\}$ are coefficients and N is the number of raingauges. A flatness constraint is imposed in estimating the coefficients and an offset value of 0.15 is used, allowing the surface to depart from gauge values. The form of log-transform of the rainfall, R, employed is log(R) for R> 4.5mm/h and (R/4.5) + log (4.5) -1 otherwise; any negative rainfalls resulting from the back-transformation are set to zero.

The estimated coefficients are used in equation (4.1) to obtain the interpolated rainfall totals on a regular 0.5 km grid: these are then used as the basis of mapping the storm rainfall fields.

4.3 ISOHYETAL MAPS OF NOTABLE STORM EVENTS

Figure 4.1 presents the maps of the notable rainfall events obtained. A map of the locations of the raingauges which registered the maximum daily total for each event does not indicate any one area which may have experienced a greater occurrence of these storms (Figure 4.2).

4.4 STORM PROFILES OF NOTABLE STORM EVENTS

The analysis of notable storm events through mapping of the daily rainfall fields has been complemented by an investigation of the storm profiles for each event. Figure 4.3 presents time series plots of the hourly rainfall in mm for those gauge sites at which the maximum daily rainfall was registered. Whilst the great variety in shapes is apparent it should be noted that twin-peaked (bimodal) profiles are not uncommon.

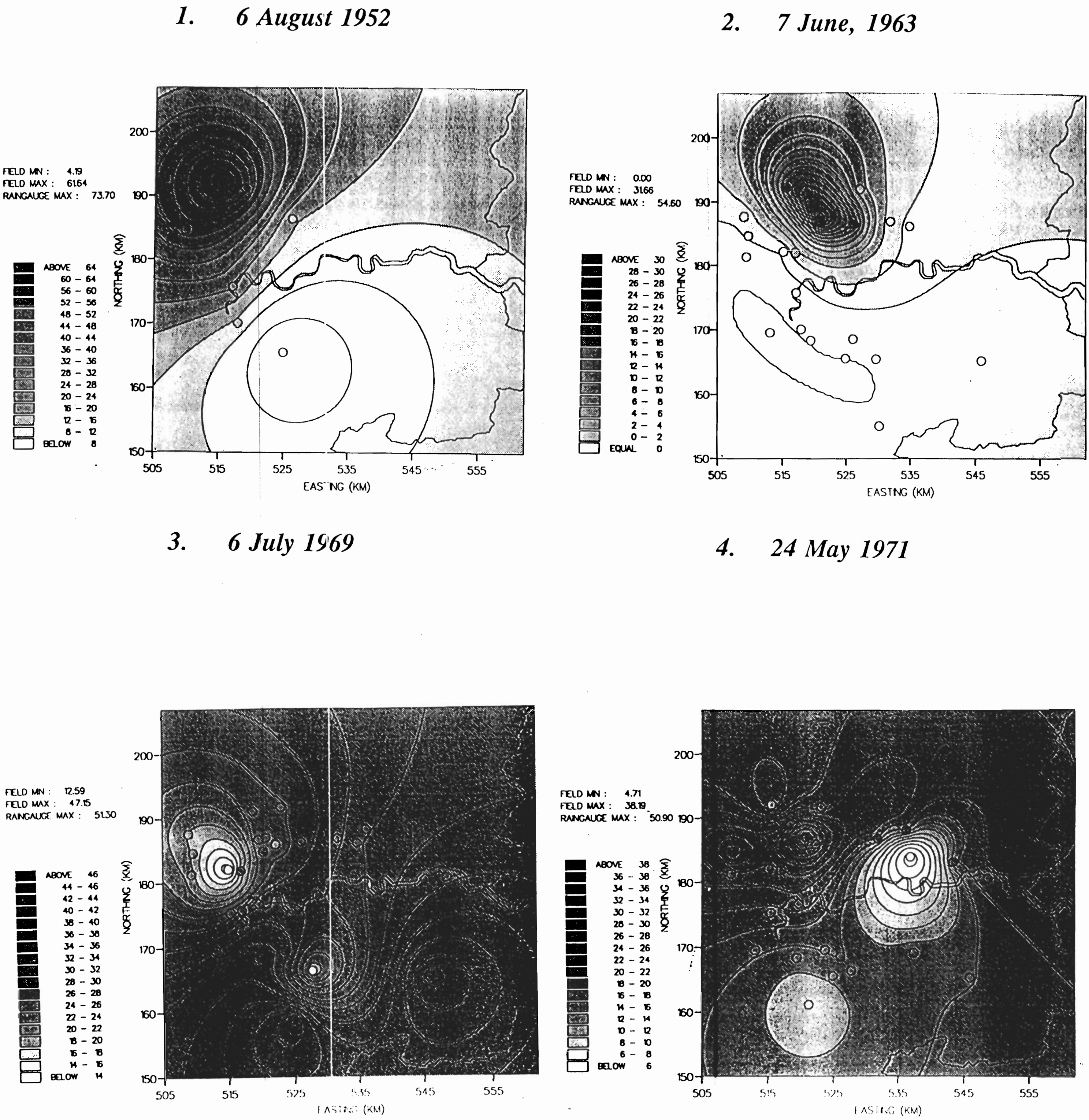
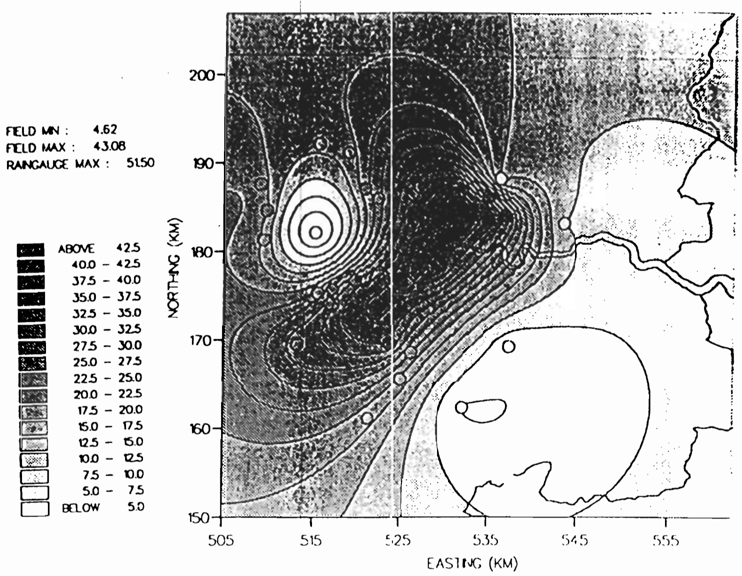
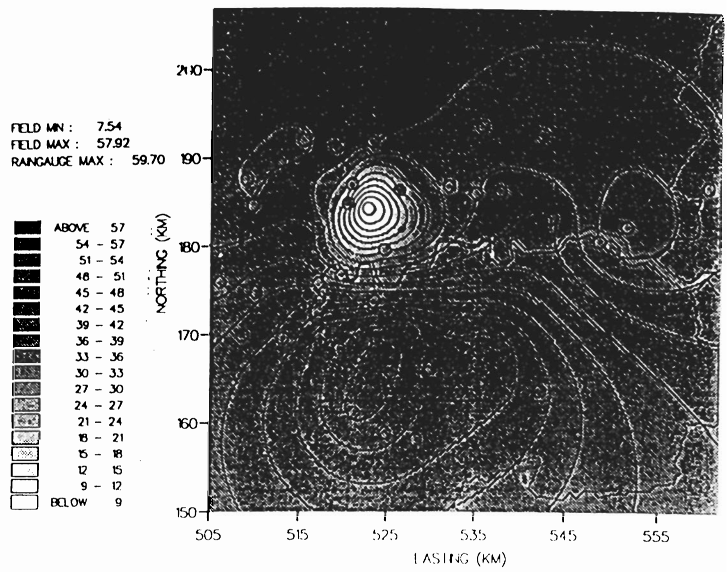


Figure 4.1 Isohyetal maps in mm of notable storm events

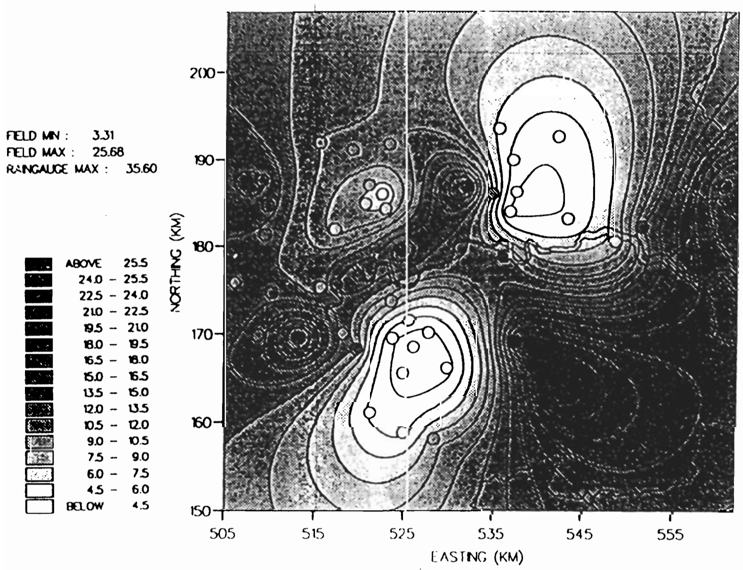
5. *4 August 1971*



6. *19 June 1973*



7. *6 July 1973*



8. *1 August 1973*

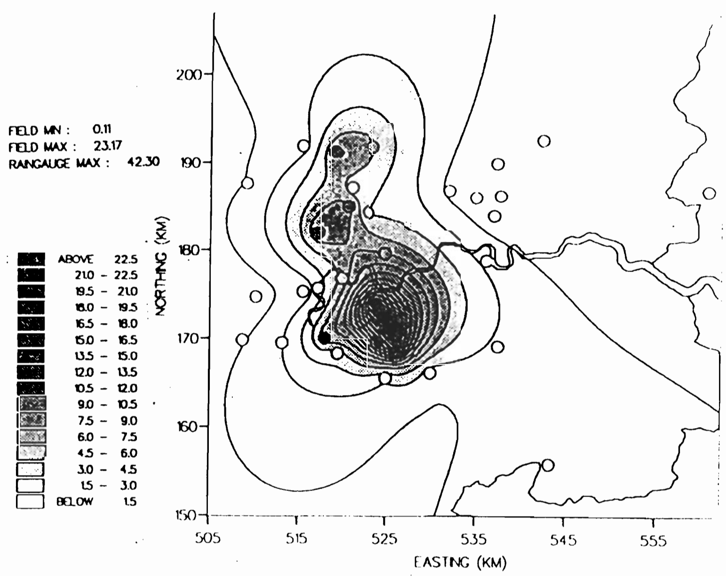
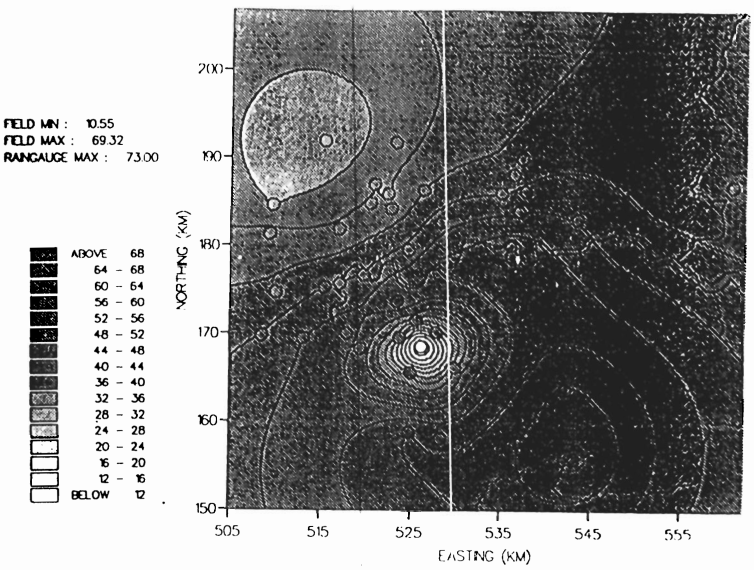
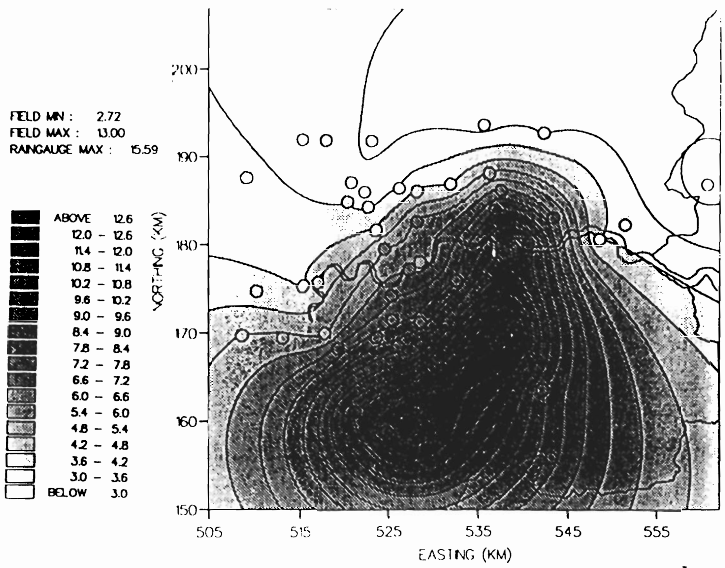


Figure 4.1 continued *Isohyetal maps in mm of notable storm events*

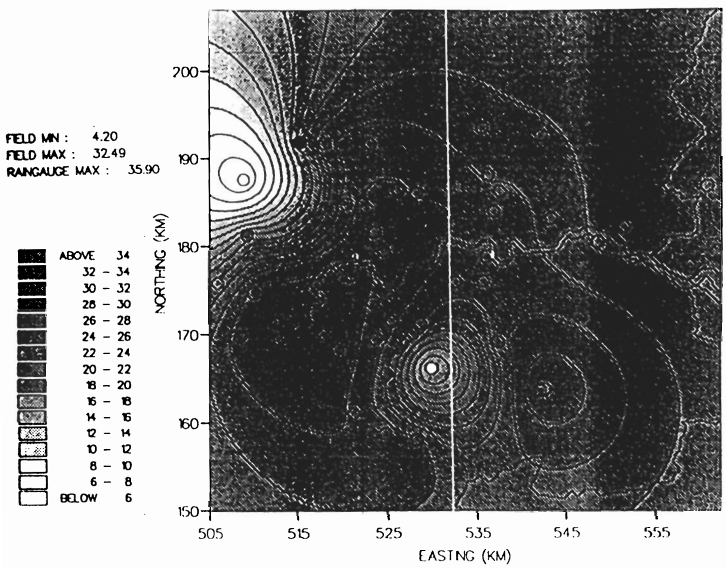
9.   20 September 1973



10.   27 June 1974



11.   4 September 1974



12.   17 November 1974

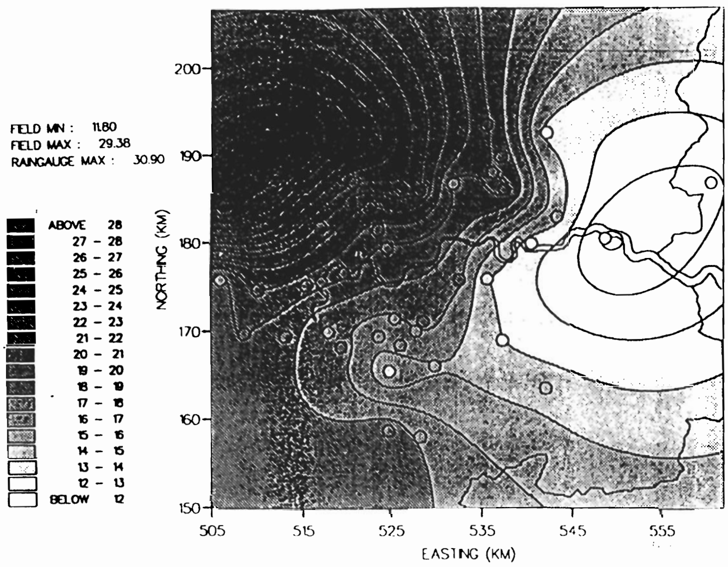
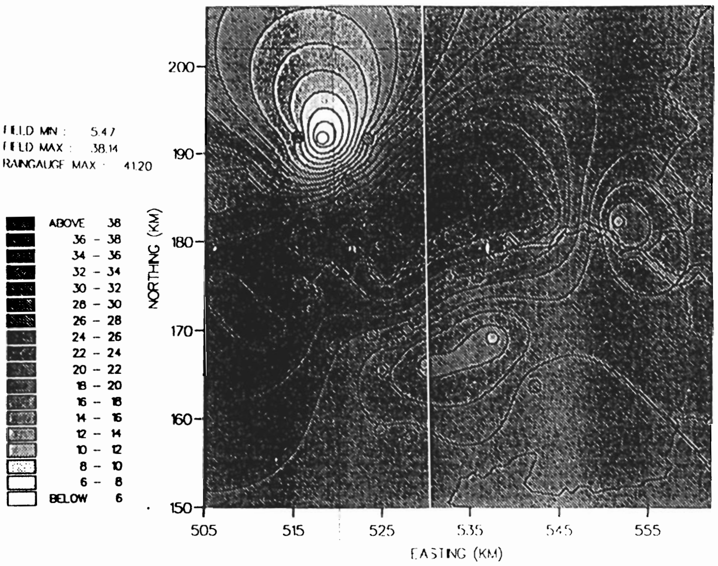
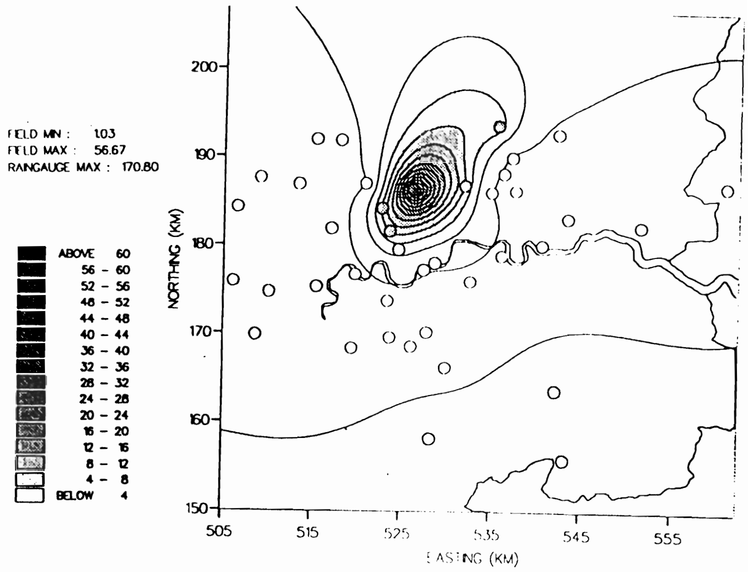


Figure 4.1 continued   *Isohyetal maps in mm of notable storm events*

13. 21 November 1974



14. 14 August 1975



15. 13 September 1975

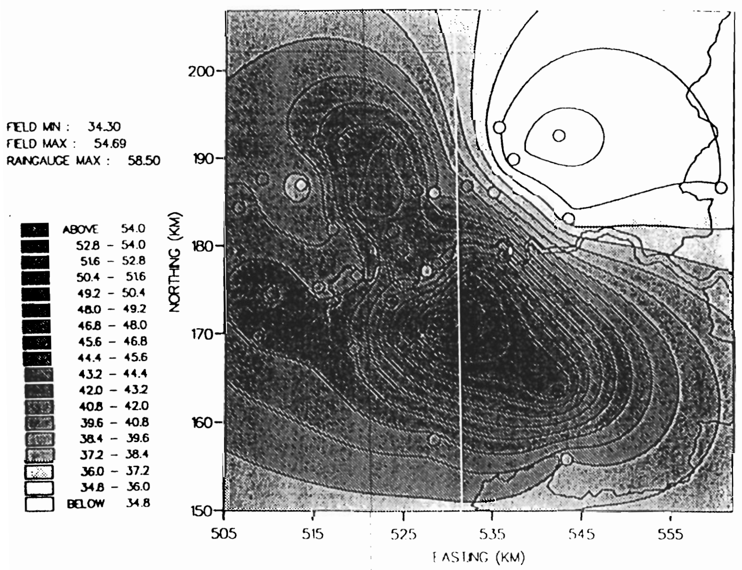


Figure 4.1 continued *Isohyetal maps in mm of notable storm events*

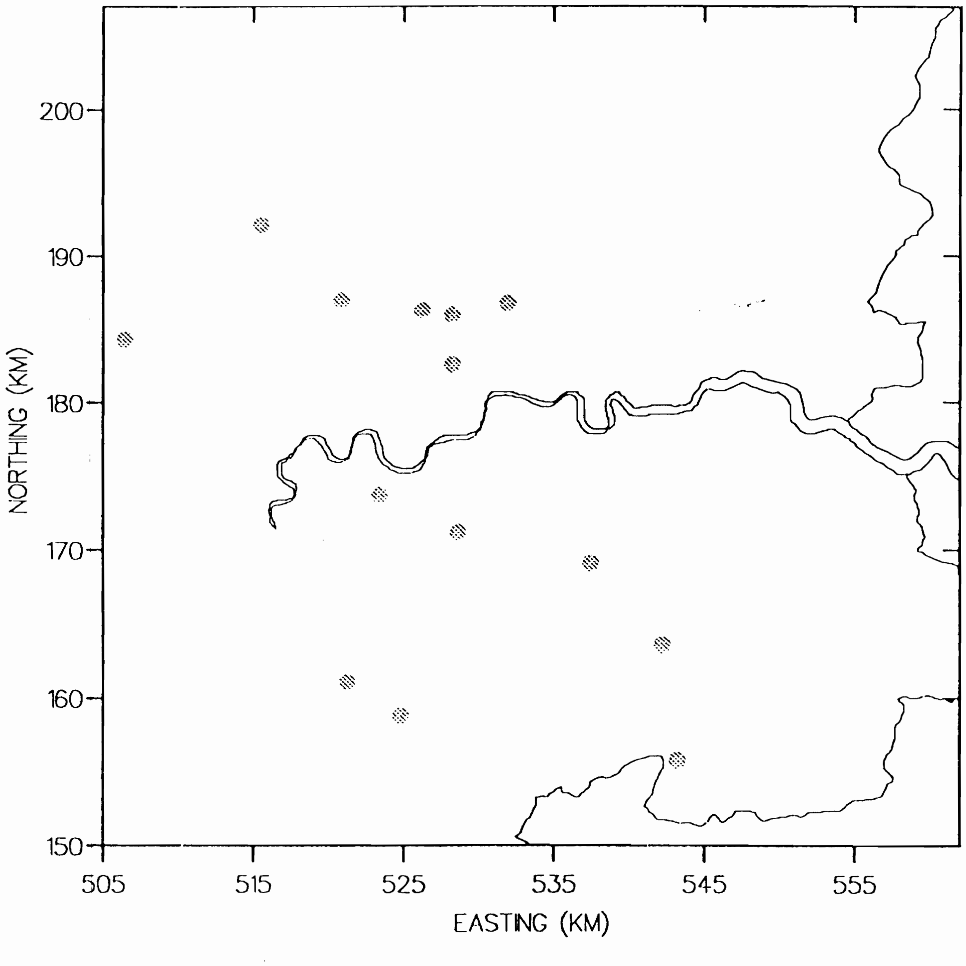
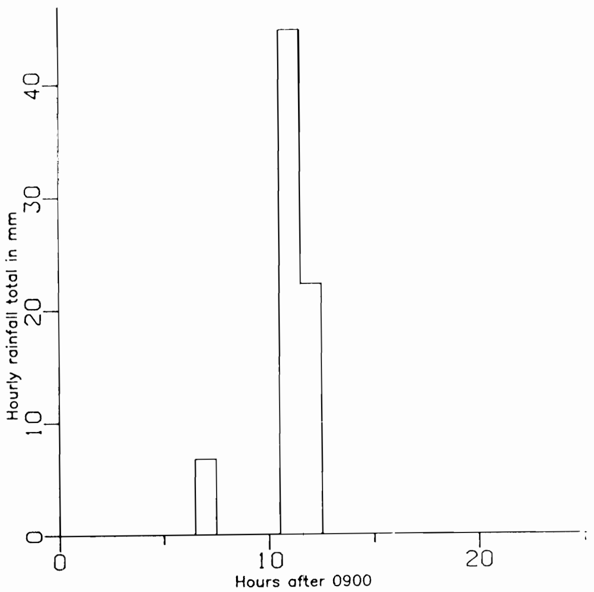
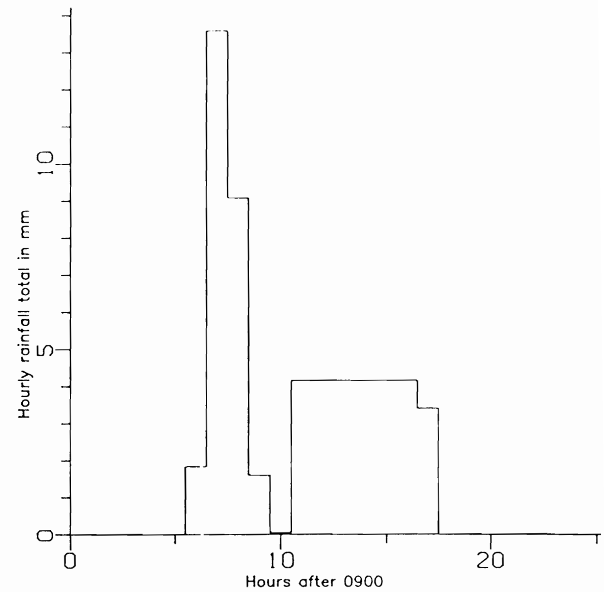


Figure 4.2 Location map of raingauges registering the maximum daily total for the notable events

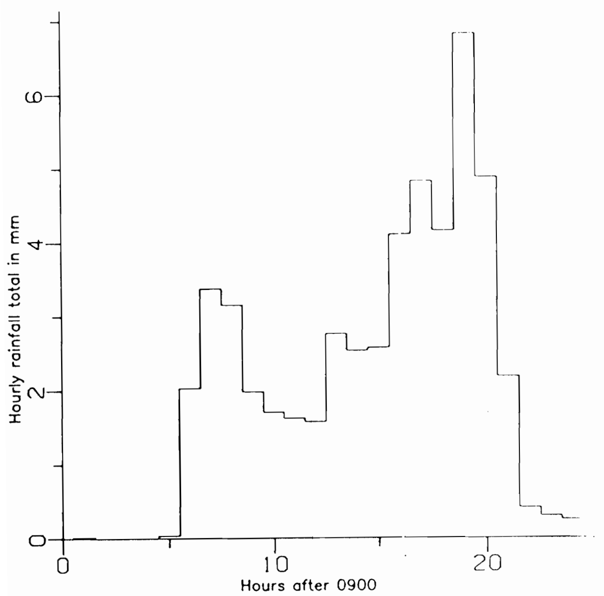
1. 6 August 1952: Stanmore



2. 7 June 1963: Brent Reservoir



3. 6 July 1969: Banstead



4. 24 May 1971: Brent Reservoir

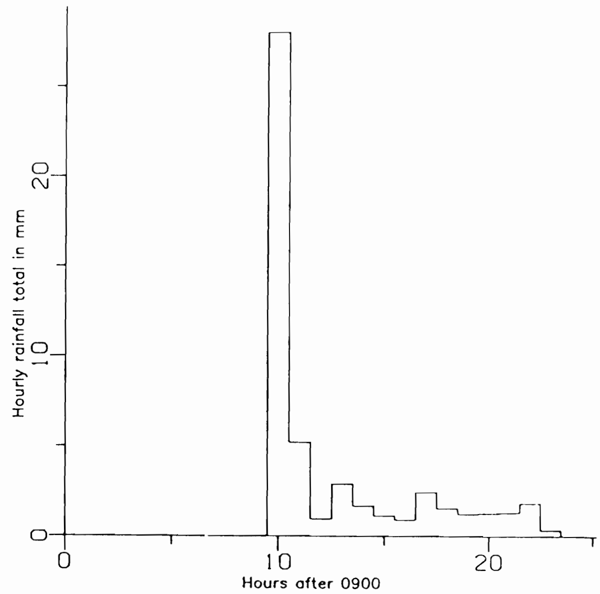
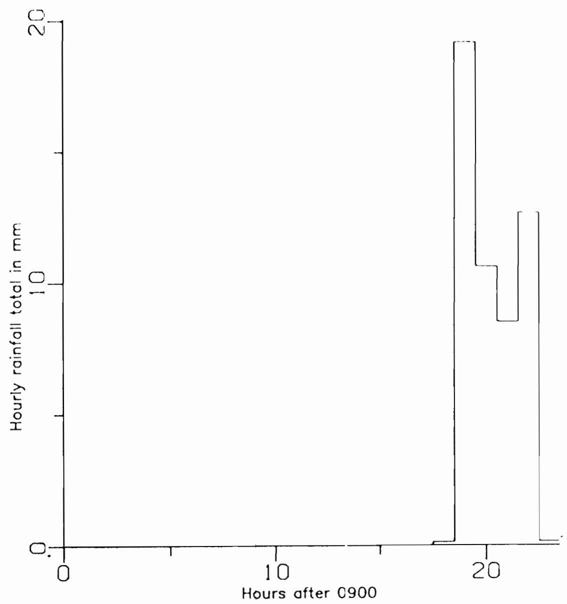
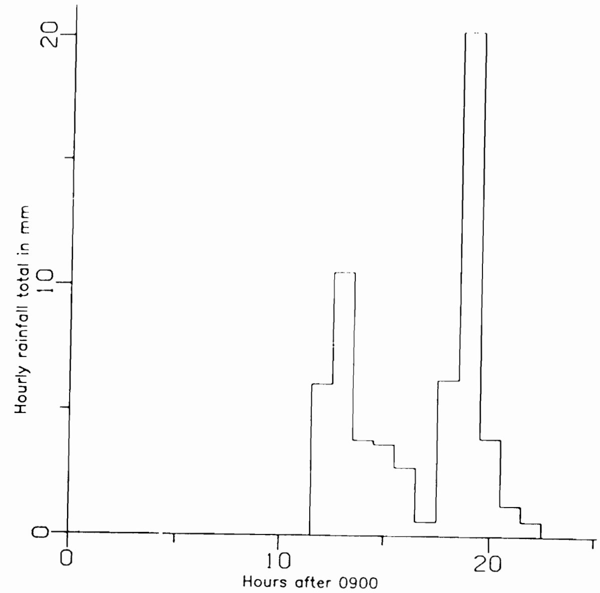


Figure 4.3 ***Time series plots of hourly rainfall for the gauge experiencing the maximum rainfall within each notable event***

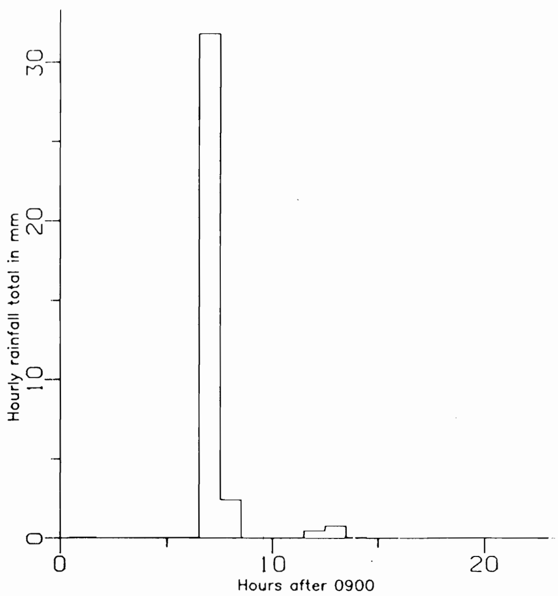
5. 4 August 1971: Western PS



6. 19 June 1973: Epsom Water Works



7. 6 July 1973: Green Lanes



8. 1 August 1973: Putney Heath

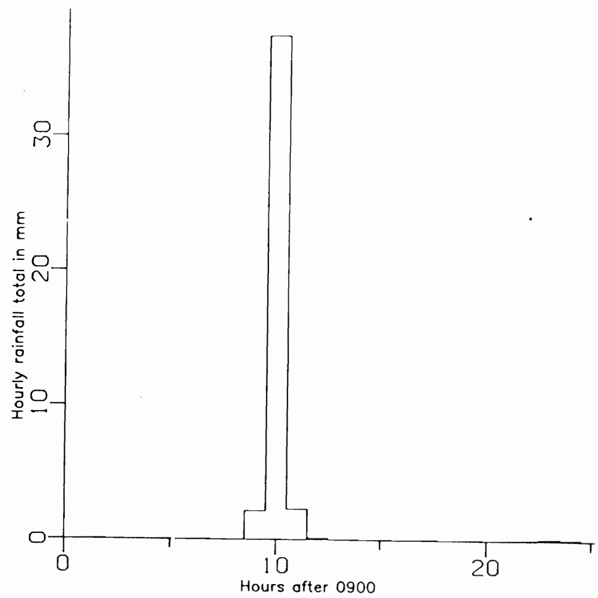
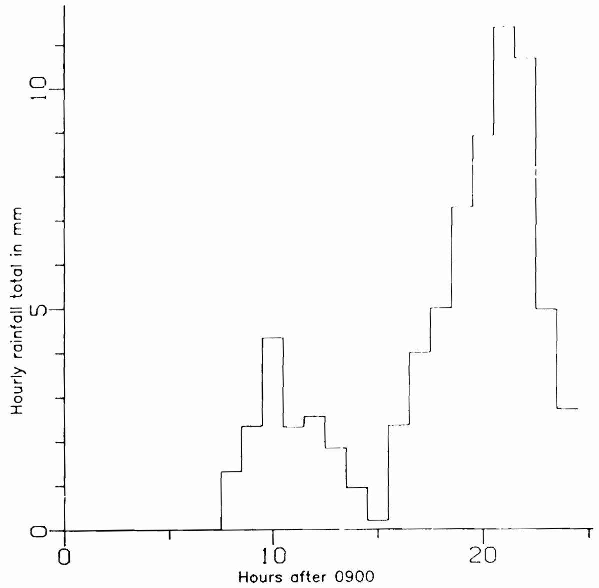
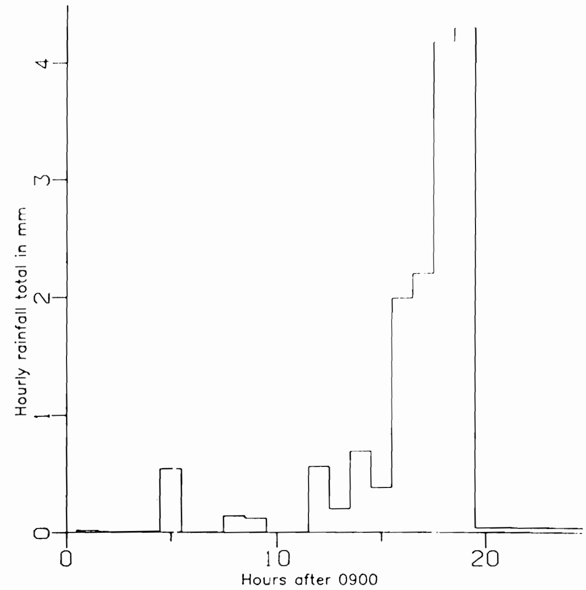


Figure 4.3 continued ***Time series plots of hourly rainfall for the gauge experiencing the maximum rainfall within each notable event***

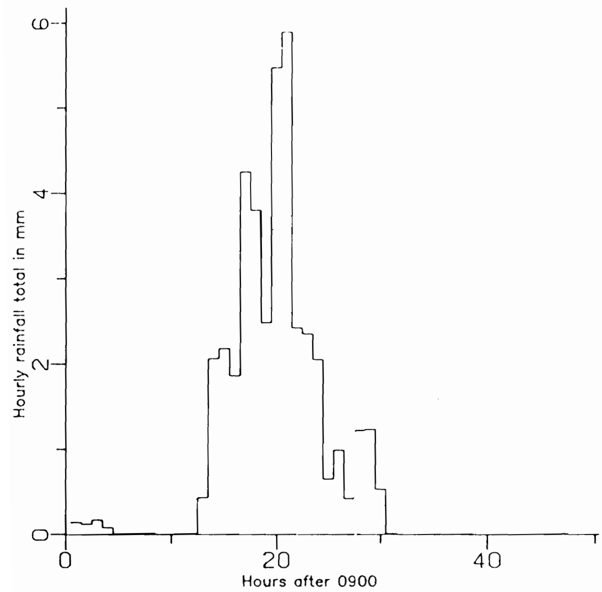
9. 20 September 1973: : Westerham Hill PS



10. 27 June 1974: Kelsey Park



11. 4 September 1974: Keston



12. 17 November 1974: Uxbridge, Honeycroft NRS

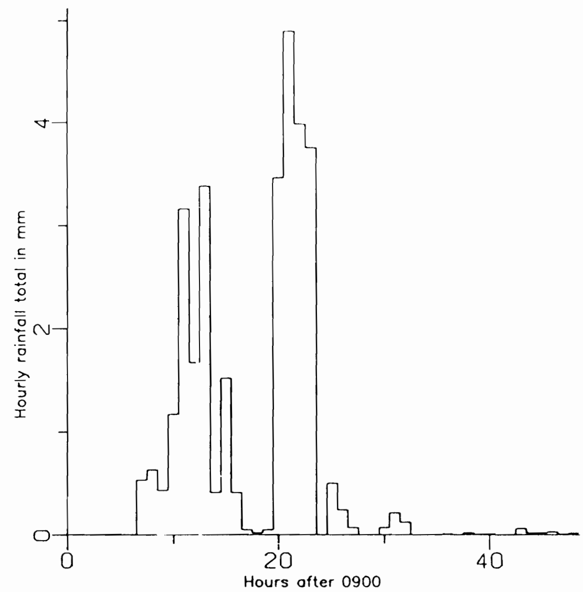
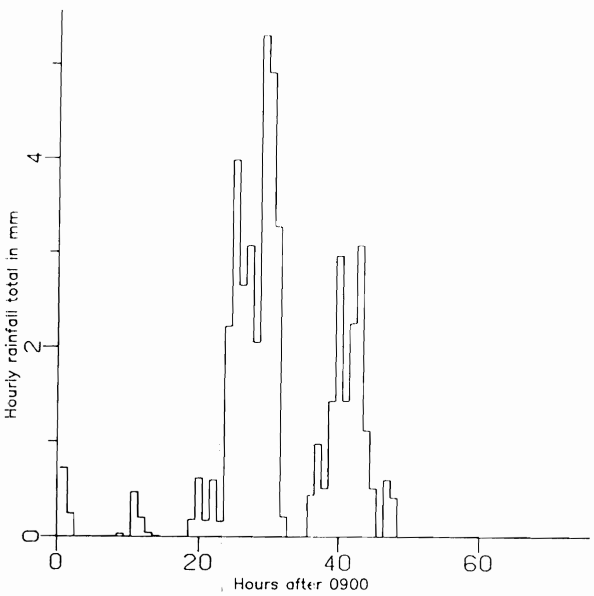
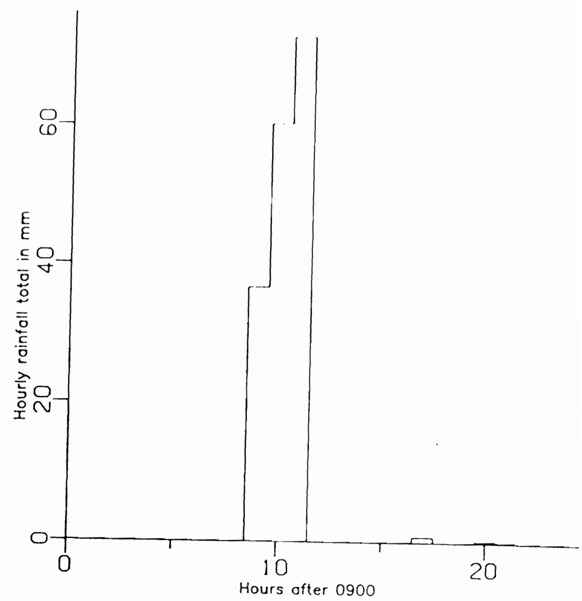


Figure 4.3 continued ***Time series plots of hourly rainfall for the gauge experiencing the maximum rainfall within each notable event***

13. 20 November 1974: Parliament Hill



14. 14 August 1975: Hampstead



15. 13 September 1975: Furzedown

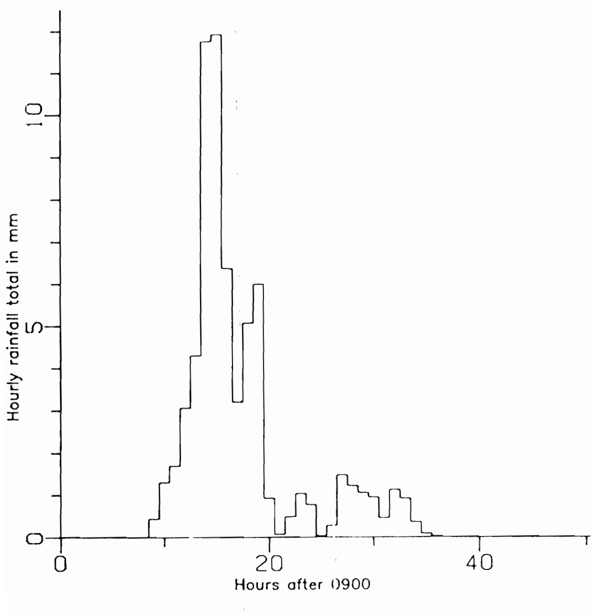


Figure 4.3 continued ***Time series plots of hourly rainfall for the gauge experiencing the maximum rainfall within each notable event***

5. Characterisation of rainfall time series

5.1 INTRODUCTION

One approach to investigating spatial storm patterns is to characterise the rainfall time series through parametric functions describing specific storm features. Mapping of the parameters then provides a means of exploring spatial variability in storm features. An extension of this approach allows a stochastic rainfall model to be formulated based on parametric functions which can form the basis of a time series approach to design storm and flood estimation.

The time series of hourly rainfall for a site can be characterised by first distinguishing between wet and dry periods and then using parametric distributions to represent the key features of each. In the case of dry periods the duration is the sole feature. For wet periods three characteristics are of primary interest: (i) the duration of the wet period, (ii) the total rainfall depth, and (iii) the shape of the storm profile. A total of 4 distributions are therefore involved, although these may be further sub-divided if any of the 4 quantities involved vary seasonally.

The wet and dry periods for a given rainfall time series are first identified. Whilst various threshold rules can be contrived to define a wet period, here the simple rule that any change from dry and wet and back again is used. Having first made this division it is then a simple matter to calculate the 4 quantities of interest, whilst keeping a record of their season of occurrence. Distributions can then be fitted and a choice made of the appropriate distribution to use in each case.

Special consideration needs to be taken of the shape of the storm profile, in terms of its profile and internal correlation structure: these issues are discussed towards the end of Section 5.

5.2 DISTRIBUTIONS OF STORM CHARACTERISTICS

Four different distributions have been considered for representing each storm characteristic: exponential, lognormal, gamma and generalised Pareto. The form of these distributions are summarised below:

(a) Exponential distribution

The probability density function is

$$f(x) = \mu^{-1} \exp(-x/\mu) \tag{5.2.1}$$

where x is the variate of interest and μ is its mean.

(b) Lognormal distribution

The probability distribution function is

$$f(x) = \frac{1}{x\sigma(2\pi)^{1/2}} \exp\left[\frac{-[\log(x/m)]^2}{2\sigma^2}\right] \tag{5.2.2}$$

where the scale parameter, m = exp μ, is the median and μ and σ are the mean and standard deviation of log x.

(c) Gamma distribution

The probability distribution function is

$$f(x) = (x/b)^{a-1}\left[\exp(-x/b)\right]/b\,\Gamma(a) \qquad a>0, b>0 \tag{5.2.3}$$

where the gamma function

$$\Gamma(a) = \int_0^\infty \exp(-u)u^{a-1}du \tag{5.2.4}$$

and a and b are the shape and scale parameters of the distribution. The mean and standard deviation of x are ab and $a^{1/2}b$.

(d) Generalised Pareto distribution.

The probability density function is

$$f(x) = a^{-1}(1-kx/a)^{1/k-1}. \tag{5.2.5}$$

$0 \leq x \leq a/k$ if $k > 0$ and $0 \leq x \leq \infty$ if $k \leq 0$ where a and k are parameters. If $k \geq -1$ the mean can be defined and is given by a/(k+1).

Sets of values for dry period duration, storm depth and storm duration were first extracted from the rainfall time series. Figures 5.2.1, 5.2.2 and 5.2.3 present the results of fitting each of the four distributions by maximum likelihood to the three storm characteristics. The results are summarised for each characteristic below.

Dry period durations

All figures indicate that lognormal and Pareto distributions give best fits with little

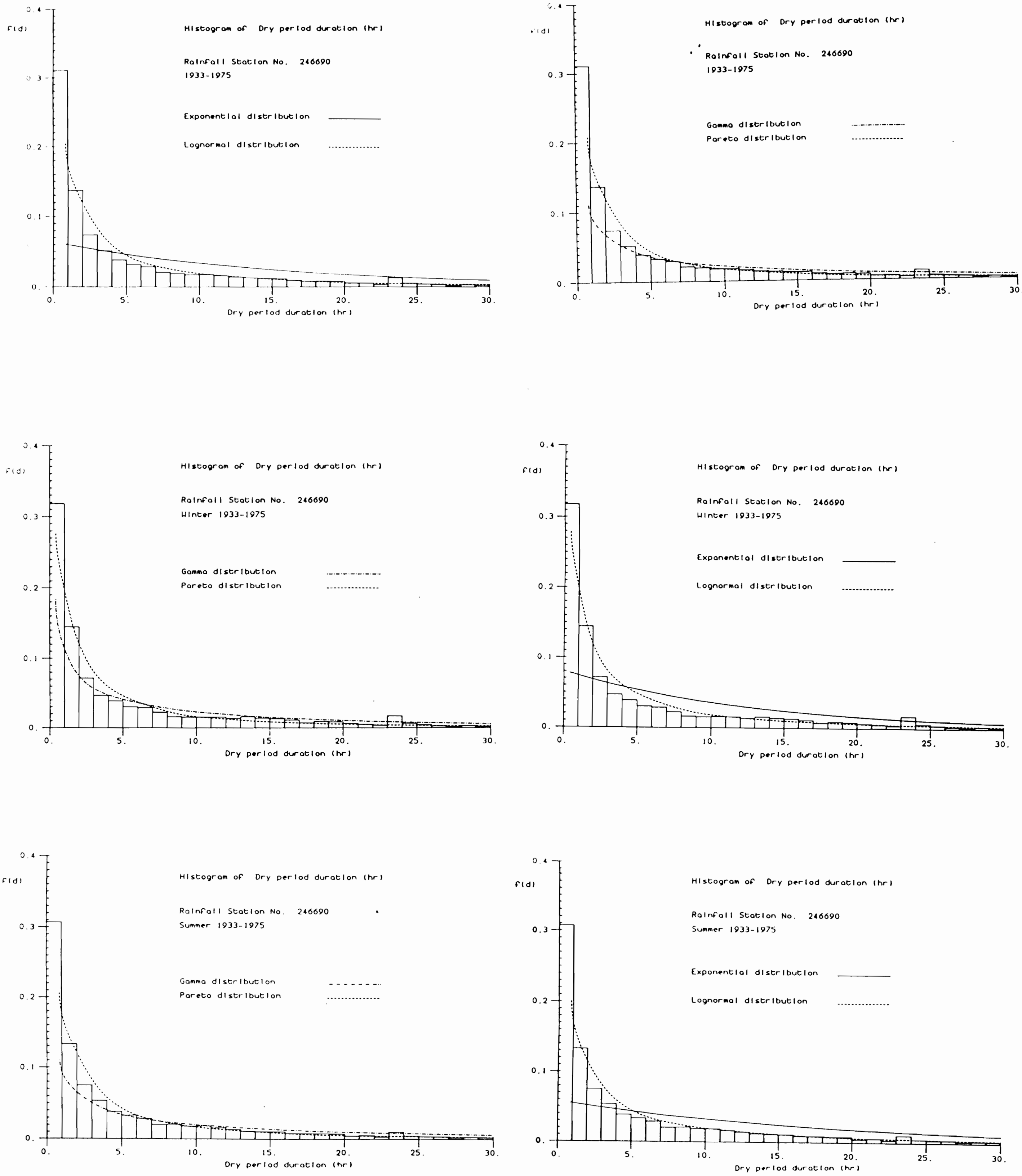


Figure 5.2.1a ***Histogram and fitted distributions of dry period durations for Hampstead.***

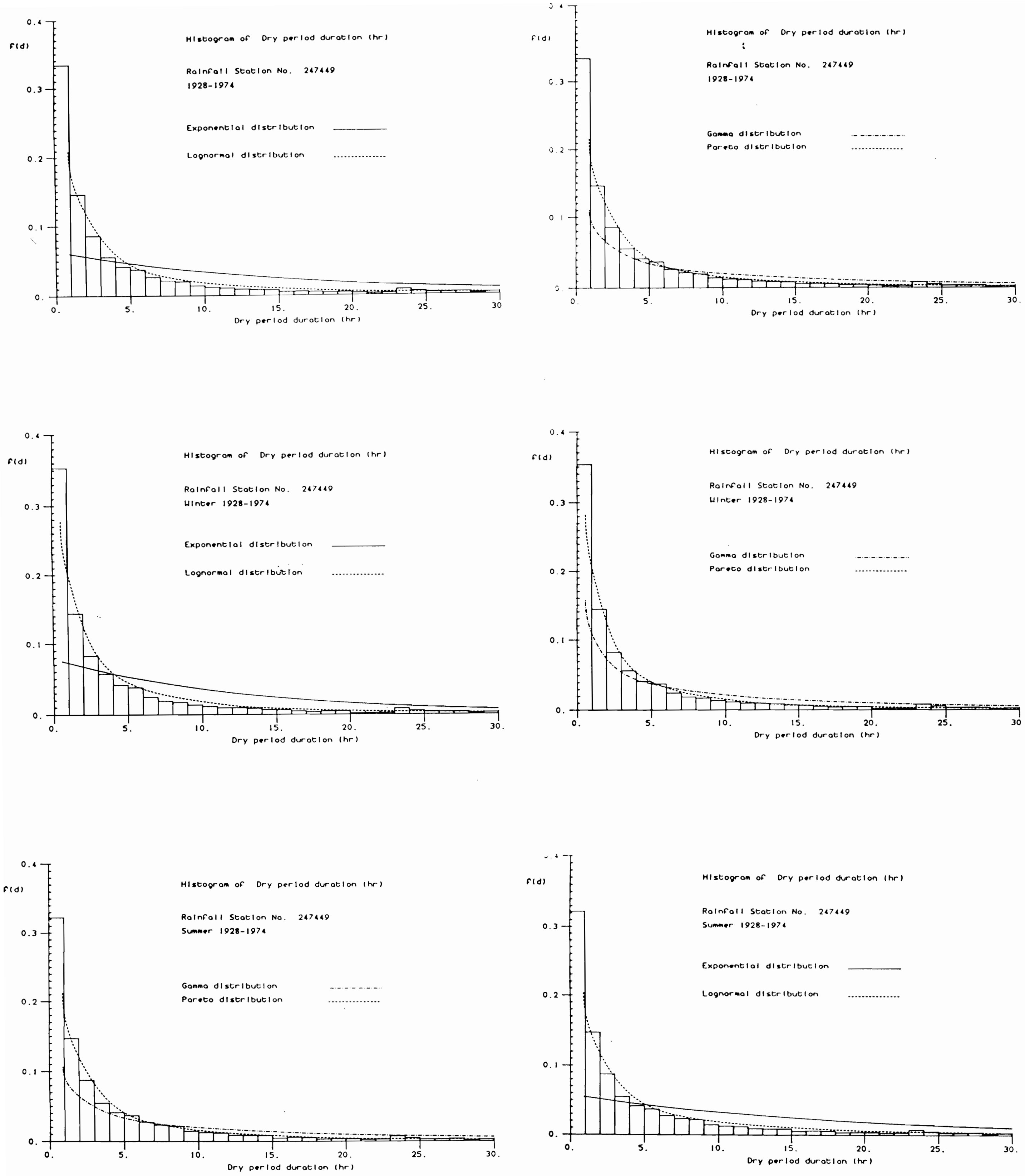


Figure 5.2.1b ***Histogram and fitted distributions of dry period durations for Hayes.***

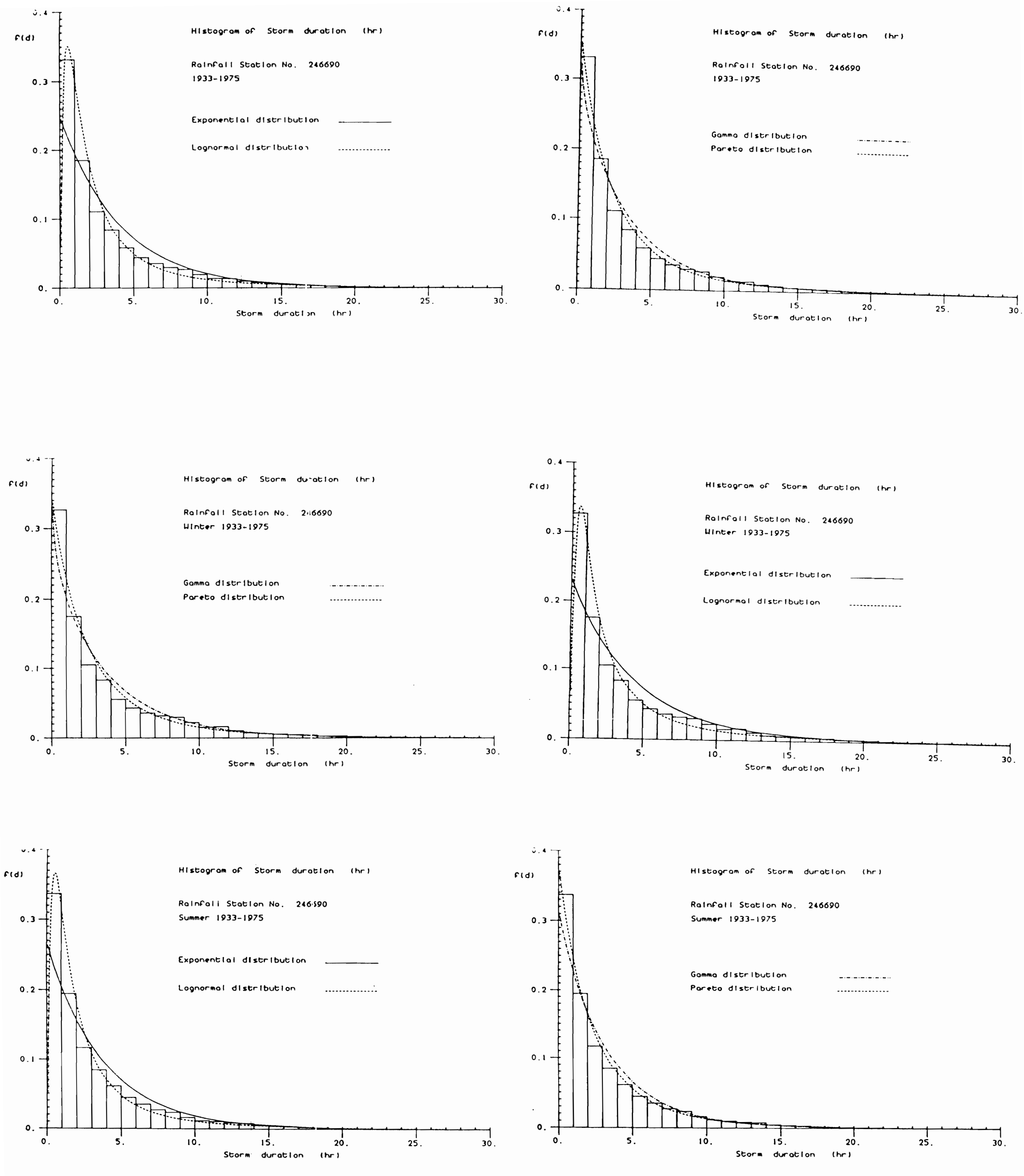


Figure 5.2.2a ***Histogram and fitted distributions of storm period durations for Hampstead.***

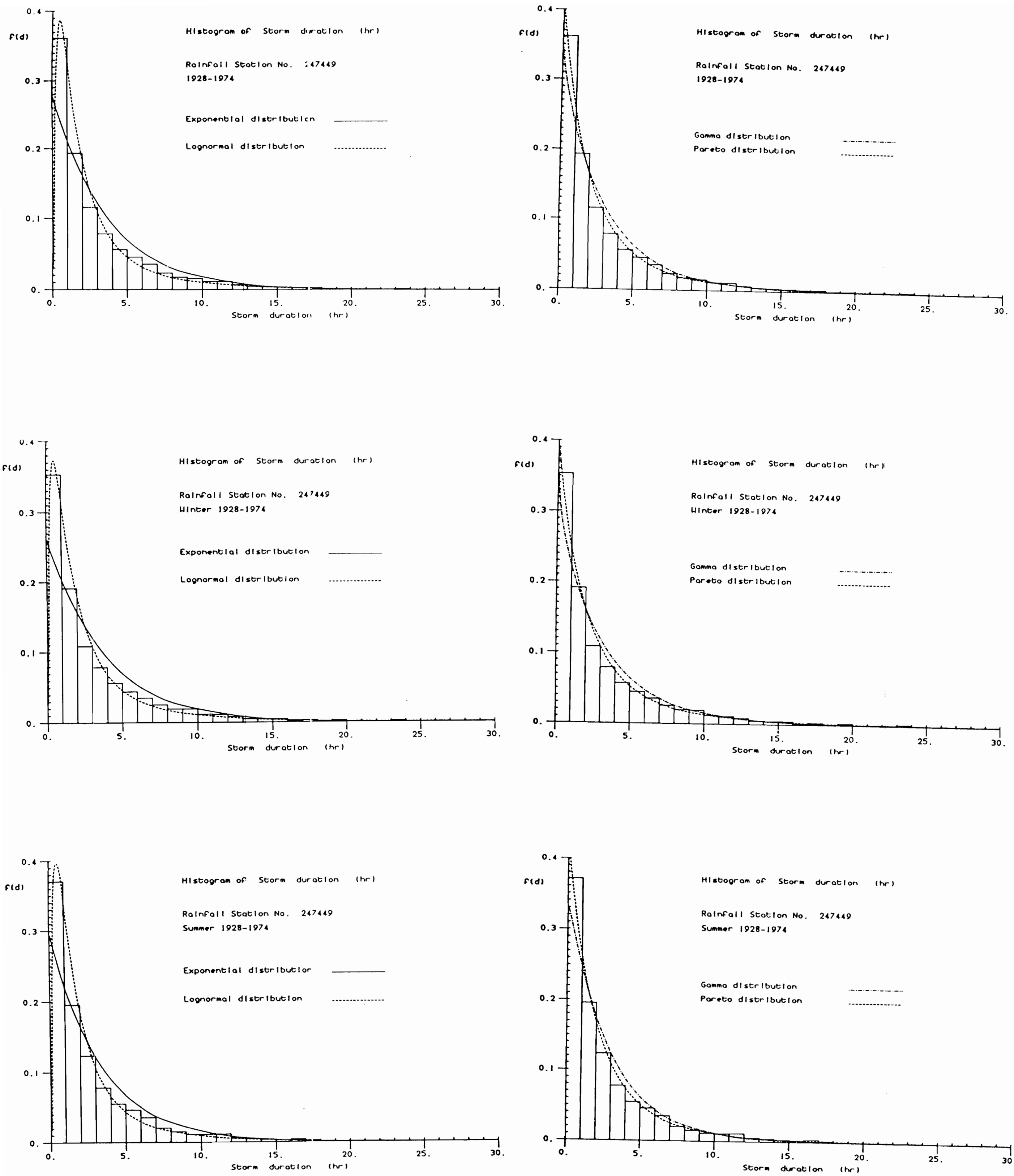


Figure 5.2.2b *Histogram and fitted distributions of storm period durations for Hayes.*

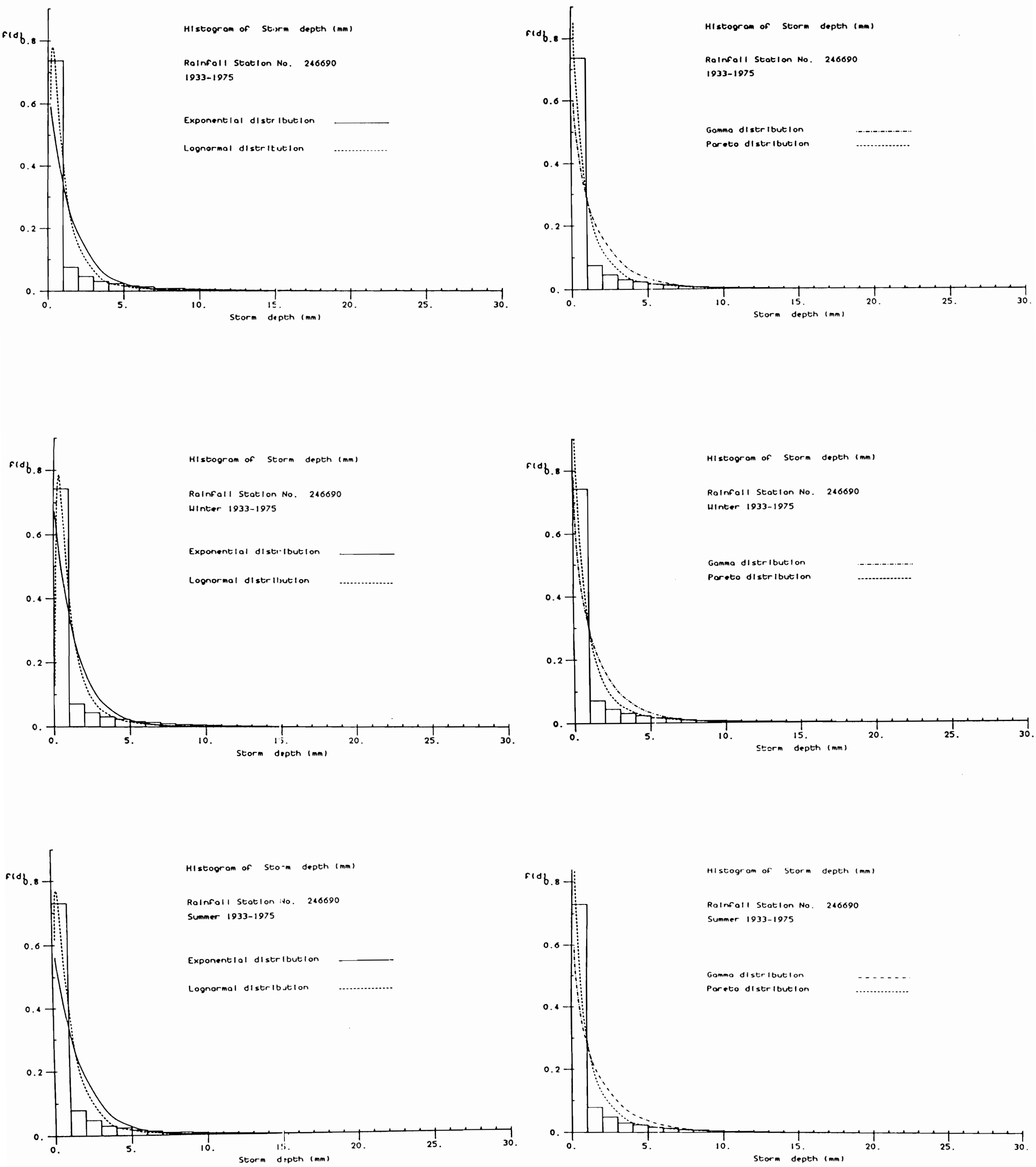


Figure 5.2.3a Histogram and fitted distribuiions of storm depth for Hampstead.

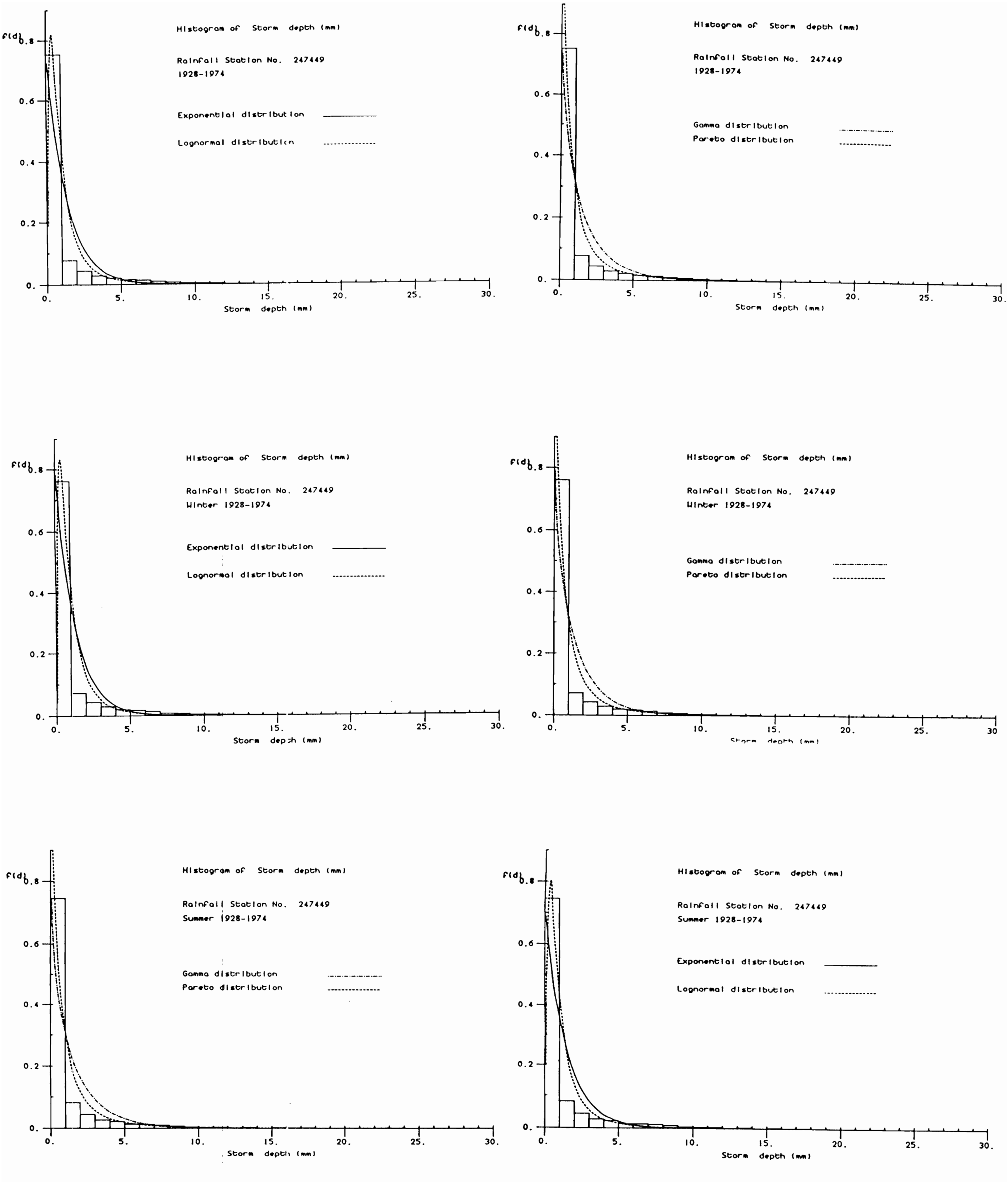


Figure 5.2.3b *Histogram and fitted distributions of storm depth for Hayes.*

to choose between them.

Storm durations

Lognormal and Pareto distributions fit well and the gamma distribution less so with the lognormal distribution being probably best overall.

Storm depths

The fit of all distributions are poor due to a very steep fall off at small depths in the empirical histograms. Overall Pareto and lognormal distributions seem to fit best.

5.3 MAPPING OF DISTRIBUTION PARAMETERS

Section 5.2 described the fitting of exponential, lognormal, gamma and generalised Pareto distributions to storm characteristics. The parameters used in these distributions can have a physical interpretation which can provide useful insights into the nature of variability from site to site. This section analyses the spatial variation in the distribution parameters for storm depths and storm durations using data from 35 raingauges over the London area. Figure 5.3, which shows the annual mean rainfall (mm) over London for the period 1941-1970, provides a useful frame of reference for the interpretation of the mapped parameters.

Storm depths

(a) Exponential distribution

The parameter μ used in this distribution is equivalent to the mean depth over all storms for a particular rainguage. Figure 5.3.1a shows the spatial plot for this parameter. A minimum occurs in the north-west corner of the square, with a maximum in the east, which corresponds to a maximum in mean storm depth. A smaller minimum occurs in the south.

(b) Lognormal distribution

The location parameter, μ, is equivalent to the mean of the log (depth), and the shape parameter, σ, is equivalent to the standard deviation of the log (depth). Figure 5.3.1b is consistent with the picture given by the exponential parameter. A maximum in storm depth is indicated on the right hand side of the square, a minimum in the top left corner and a less pronounced minimum in the south. There seems to be more deviation from the mean with increasing depth.

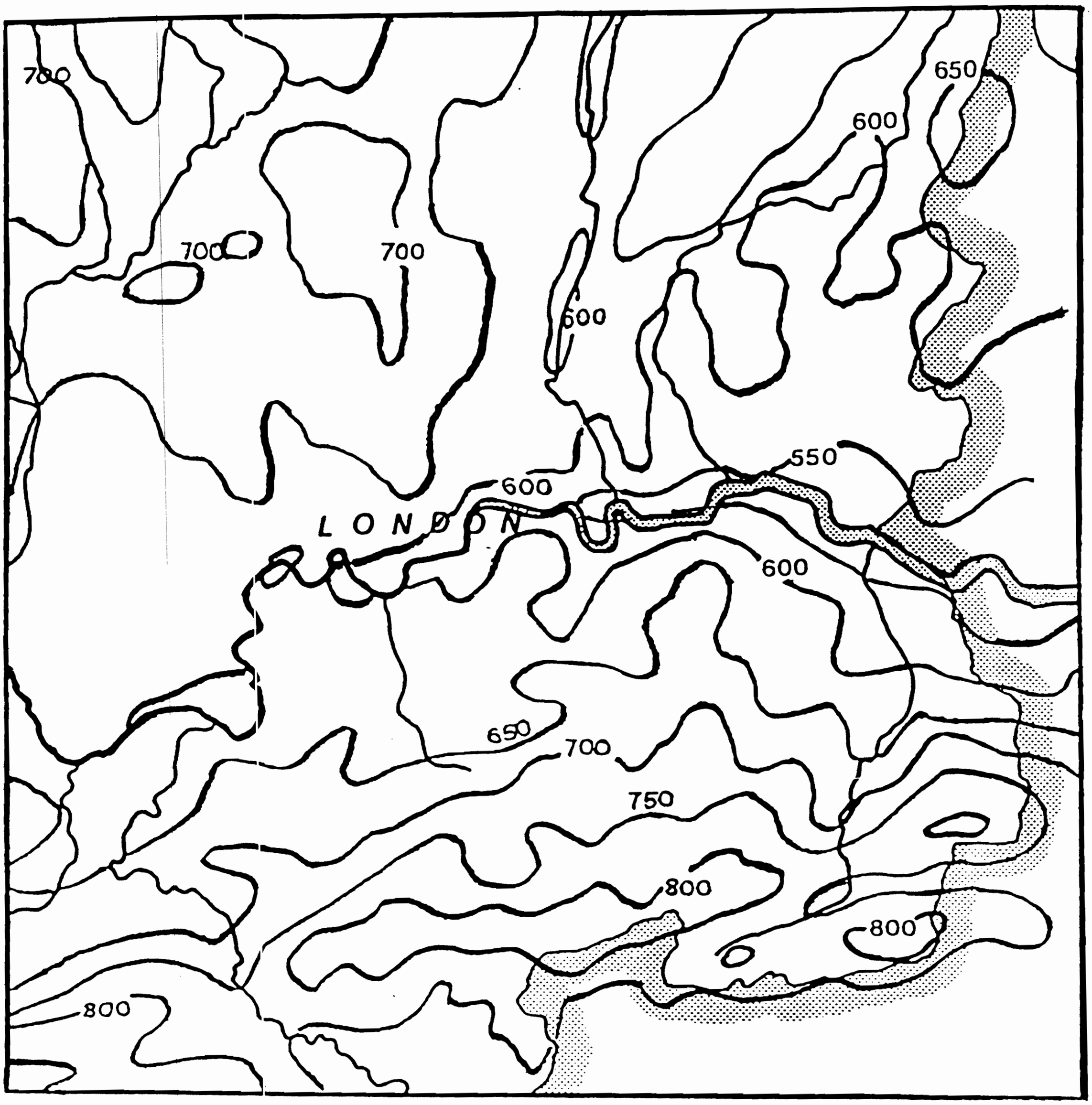


Figure 5.3 Annual mean rainfall (mm) over London 1941-1970.

Mean, μ

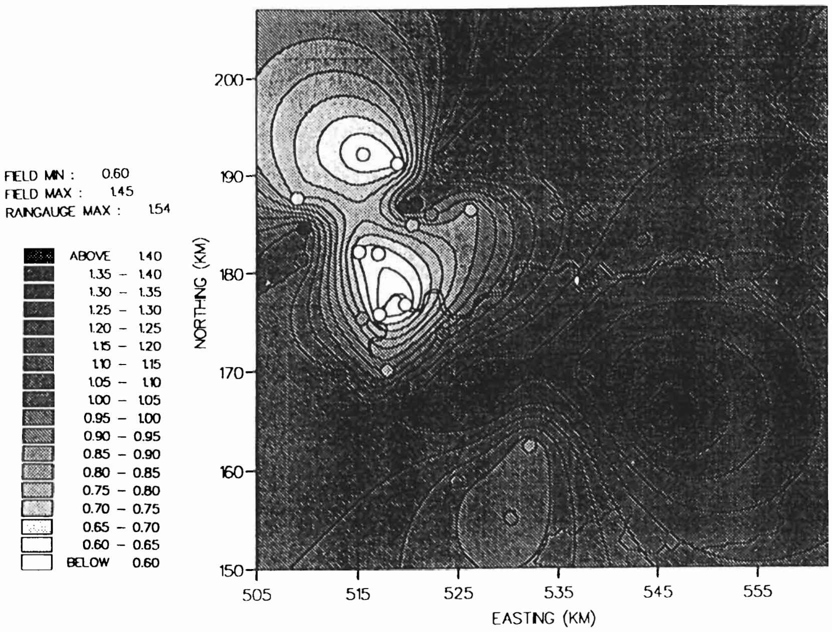
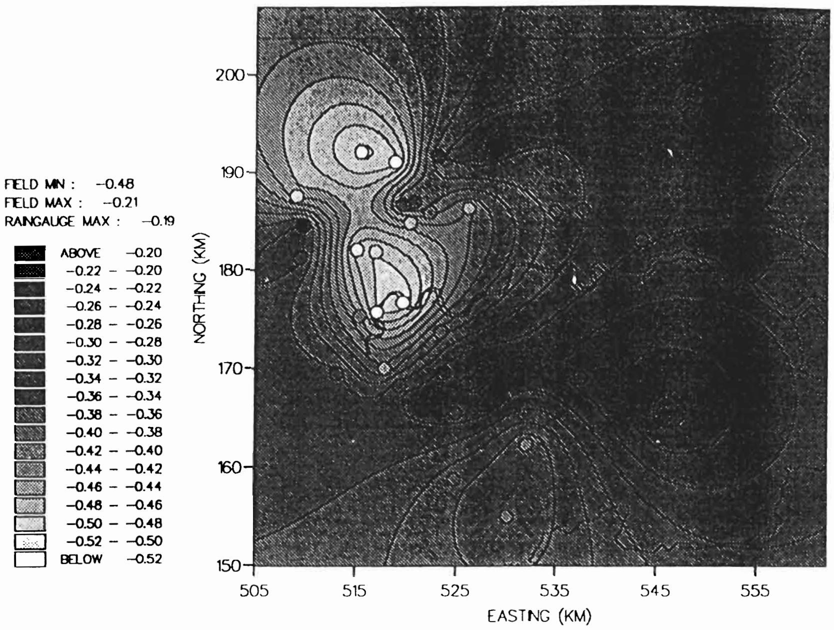


Figure 5.3.1a ***Mapping of storm depth distribution parameters: exponential distribution***

Location parameter, μ



Shape parameter, σ

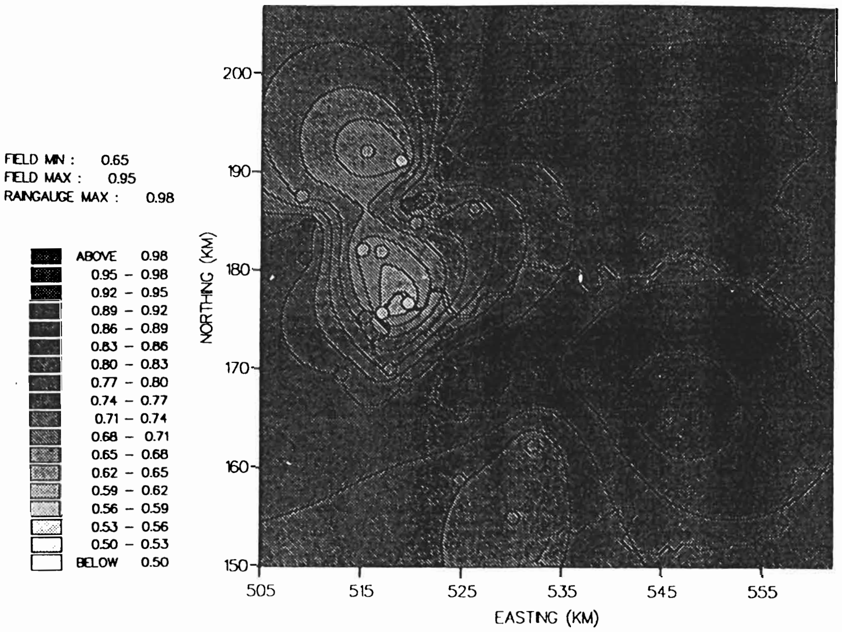
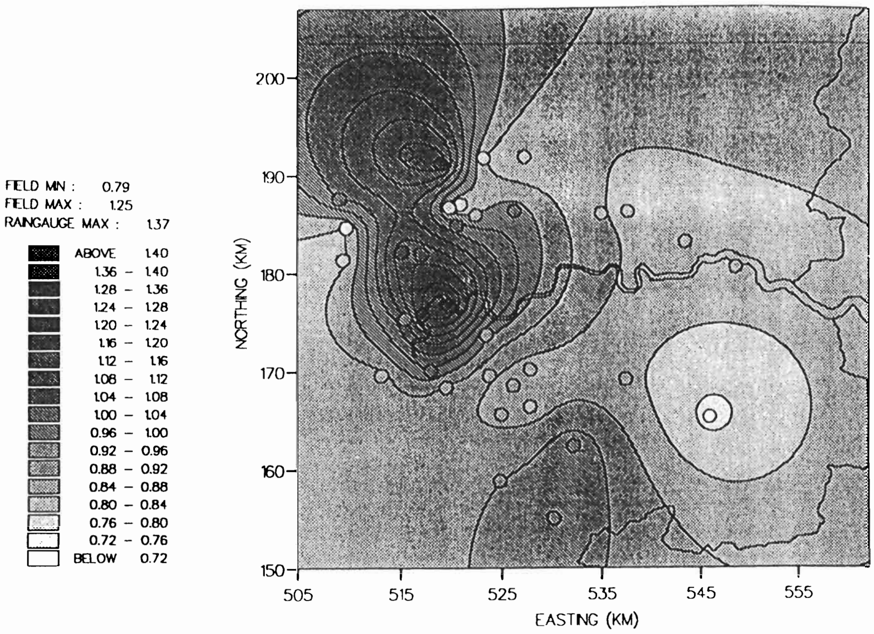


Figure 5.3.1b ***Mapping of storm depth distribution parameters: lognormal distribution***

Shape parameter, a



Scale parameter, b

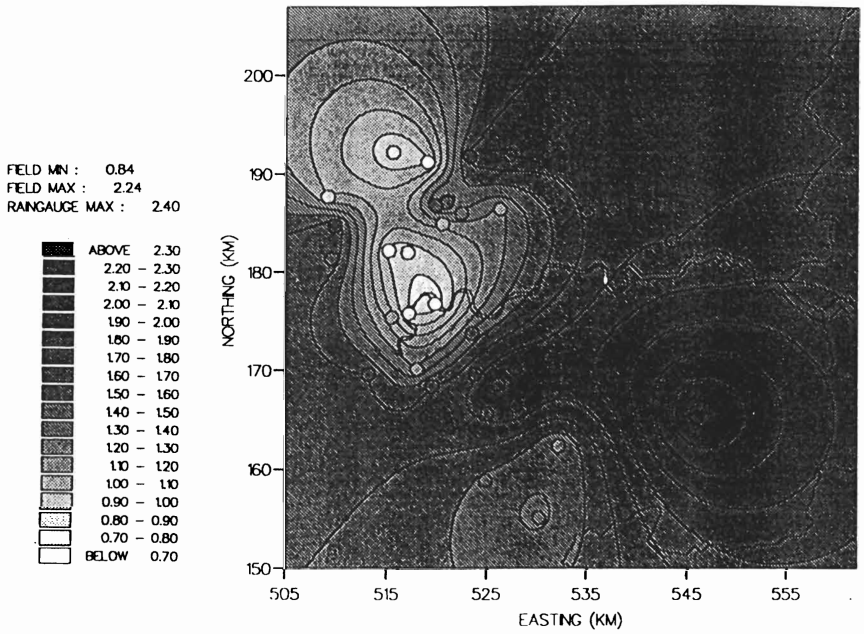
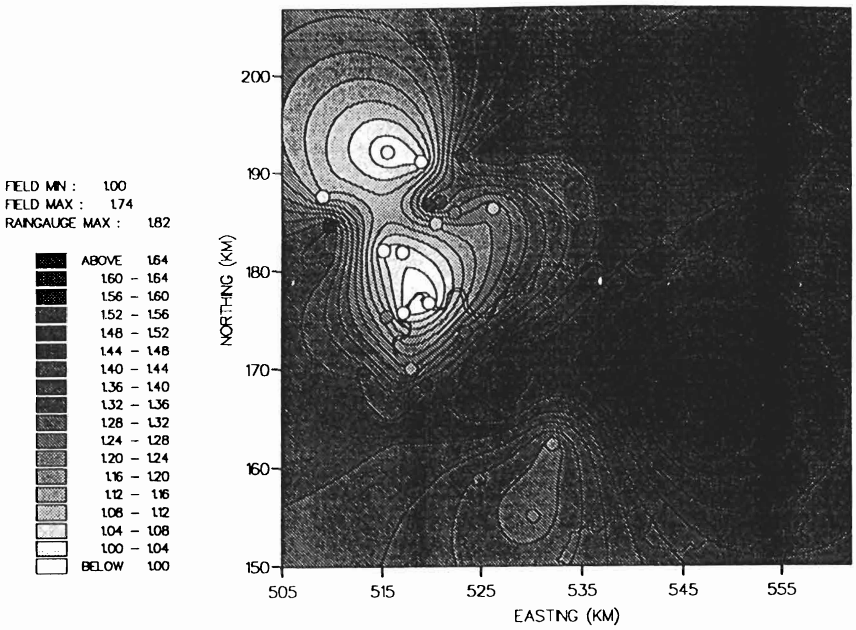


Figure 5.3.1c ***Mapping of storm depth distribution parameters: Gamma distribution***

Mean, ab



Standard deviation, $a^{1/2}b$

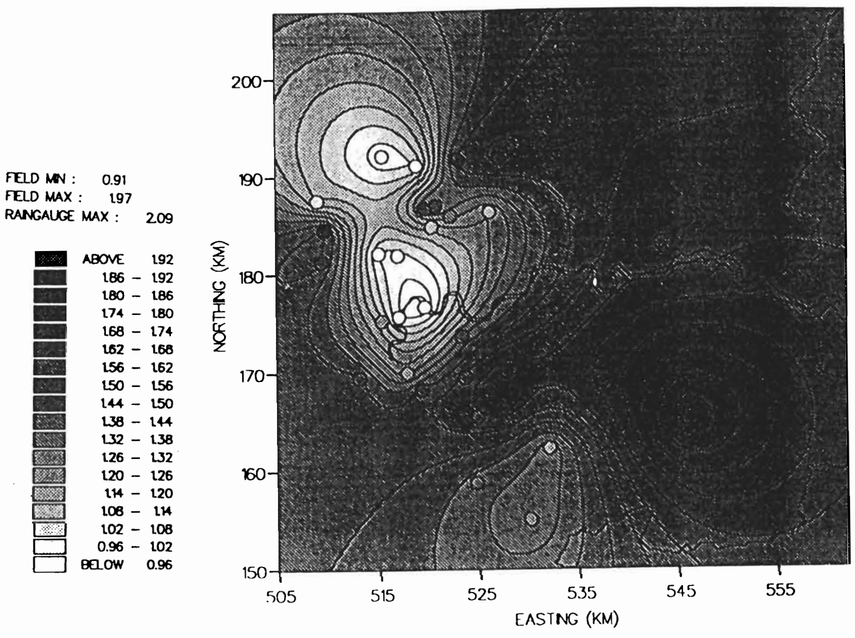
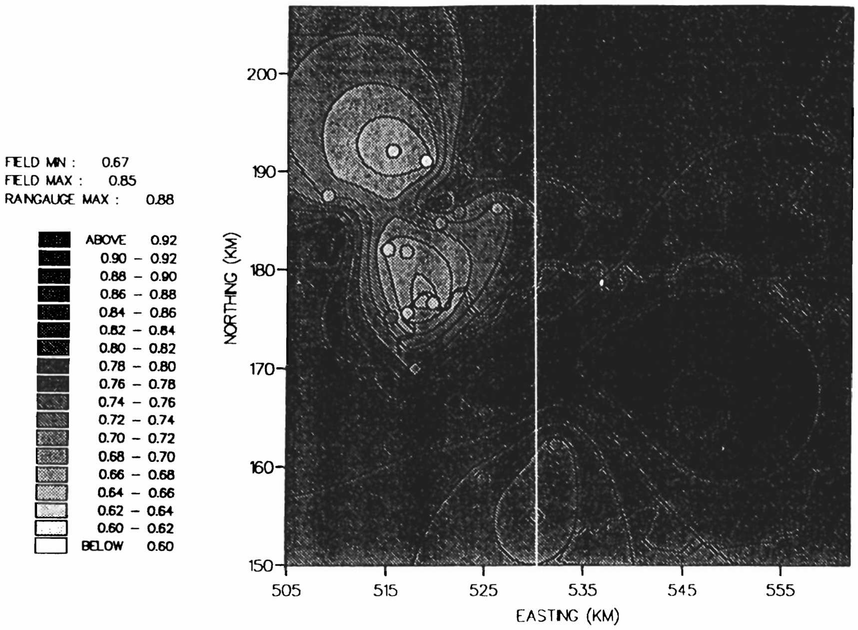


Figure 5.3.1d ***Mapping of storm depth distribution parameters: Gamma distribution***

Parameter a



Parameter k

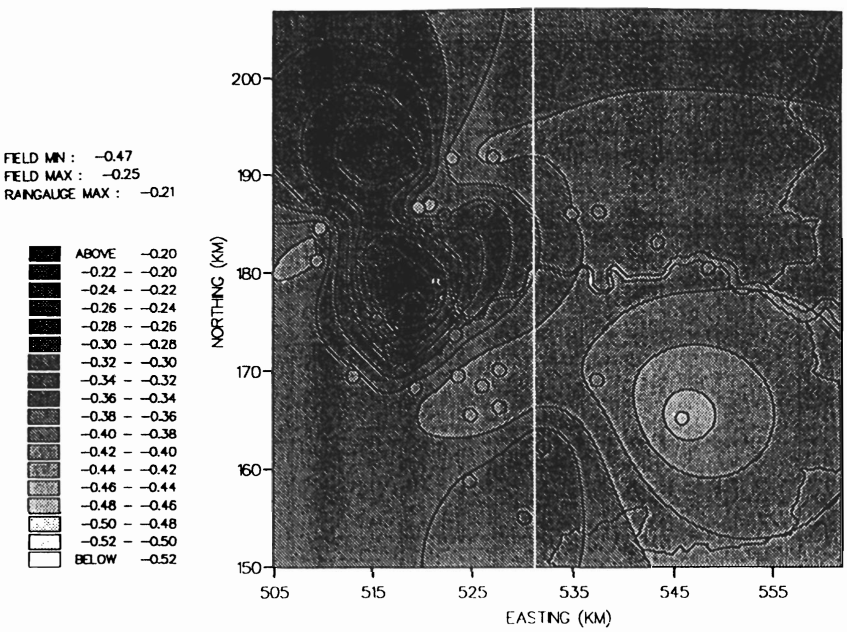


Figure 5.3.1e ***Mapping of storm depth distribution parameters: Generalised Pareto distribution***

Mean, a/(k+1)

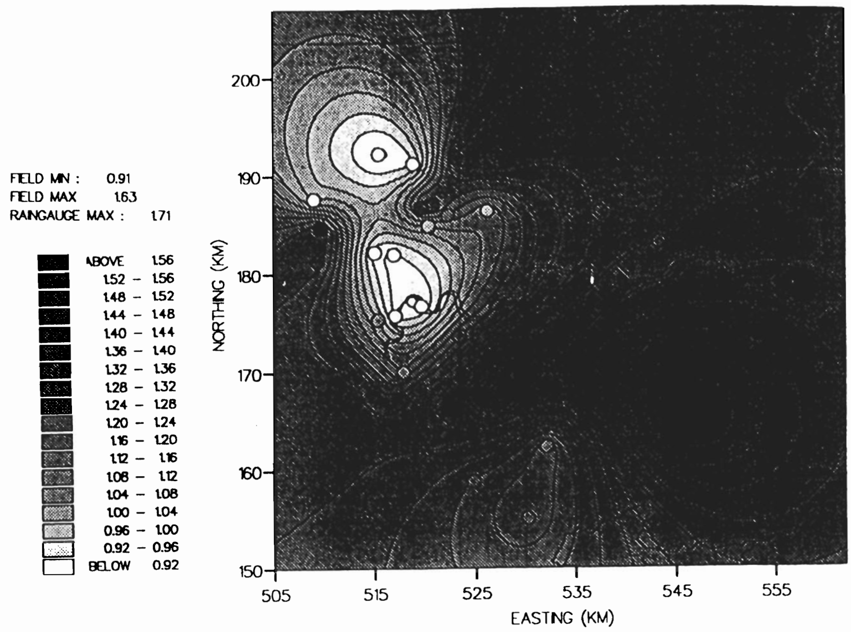


Figure 5.3.1f ***Mapping of storm depth distribution parameters: Generalised Pareto distribution***

(c) Gamma distribution

The product of the two parameters, ab, in this distribution is equivalent to the mean storm depth and the product of the square root of the shape parameter and the scale parameter, $a^{1/2}b$, is equivalent to the standard deviation of the storm depths. The parameters are mapped in Figures 5.3.1c and d: patterns are similar to previous distributions with maximum and minimum mean storm depths and deviations from the mean, indicated in similar areas.

(d) Generalised Pareto distribution

The mean of the generalised Pareto distribution is equal to $a/(k+1)$ for $k>-1$. Figure 5.3.1e presents spatial plots of a and k and Figure 5.3.1f a spatial plot of $a/(k+1)$. It can be seen that as with plots of the other parameters, minima occur in the north-west corner and on the south side and there is a maximum on the east side implying lower storm depths on average in the north-west and south than in the east. The parameter k determines the shape of the distribution: the closer its value is to zero (i.e. if it is negative, as here) the higher the probability of small depth storms and the more steep the drop-off in frequency, with increasing depth. In this case k is closest to zero in the north-west and south, implying again a bias towards storms with smaller depths in these areas. The parameter k is always negative for these gauges, which means that all distributions in this case are unbounded (i.e. rainfall depth does not asymptote to a maximum value).

Storm durations

(a) Exponential distribution

The parameter, μ, in this case is equivalent to the mean duration (Figure 5.3.2a). The general pattern is similar to that for storm depths except in this case μ is lower in the north-west and south, than in the east, implying longer duration, lighter storms on average in the north-west and south, and shorter durations, heavier storms, on average in the east.

(b) Lognormal distribution

The patterns of parameter variation shown in Figure 5.3.2b is similar to that in the exponential case. In addition, higher standard deviations are implied with increasing storm duration.

(c) Gamma distribution

The patterns are similar and consistent with those in (a) and (b) (see Figure 5.3.2 c and d).

(d) Generalised Pareto distribution.

Figures 5.3.2e and f present plots of a,k, and $a/(k+1)$. In general, the patterns are

Mean, μ

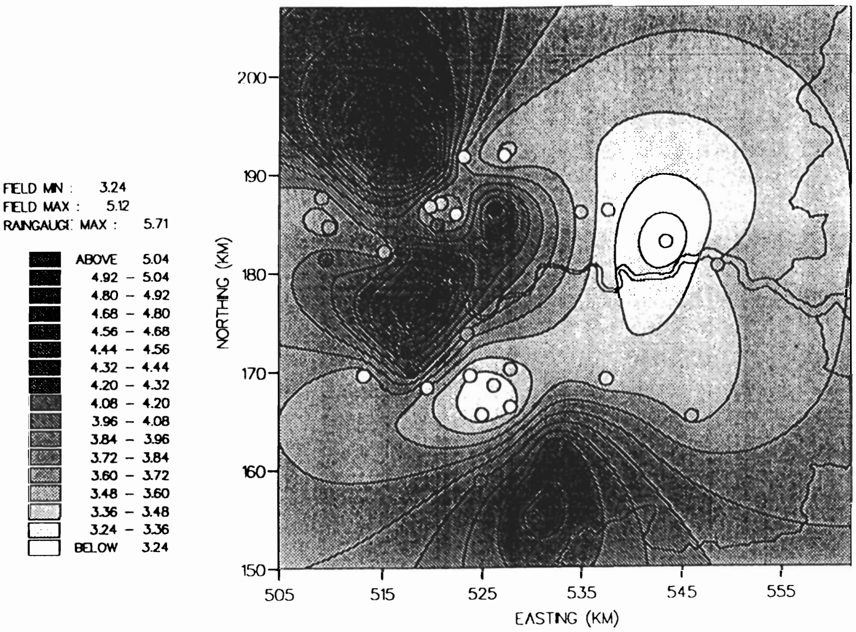
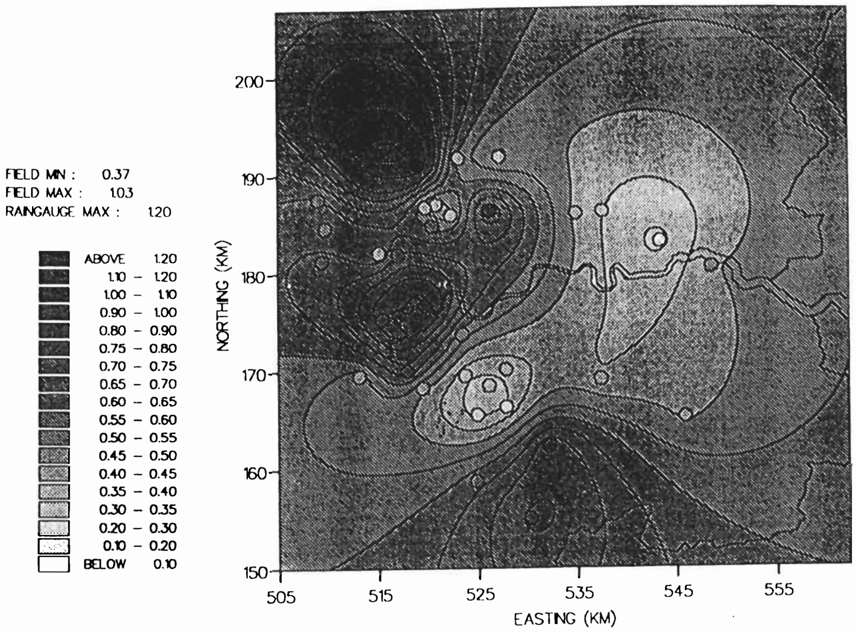


Figure 5.3.2a ***Mapping of storm duration distribution parameters: Exponential distribution***

Mean, μ



Standard deviation, σ

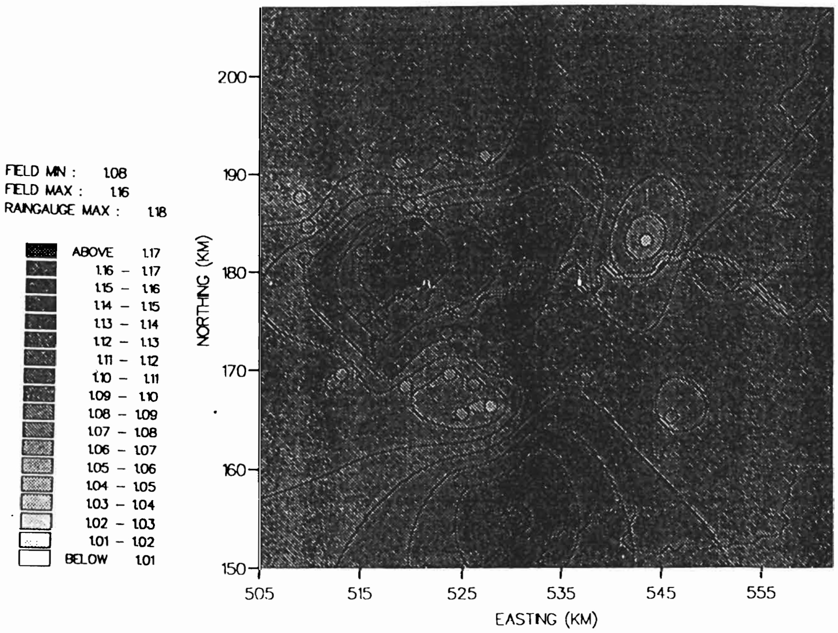
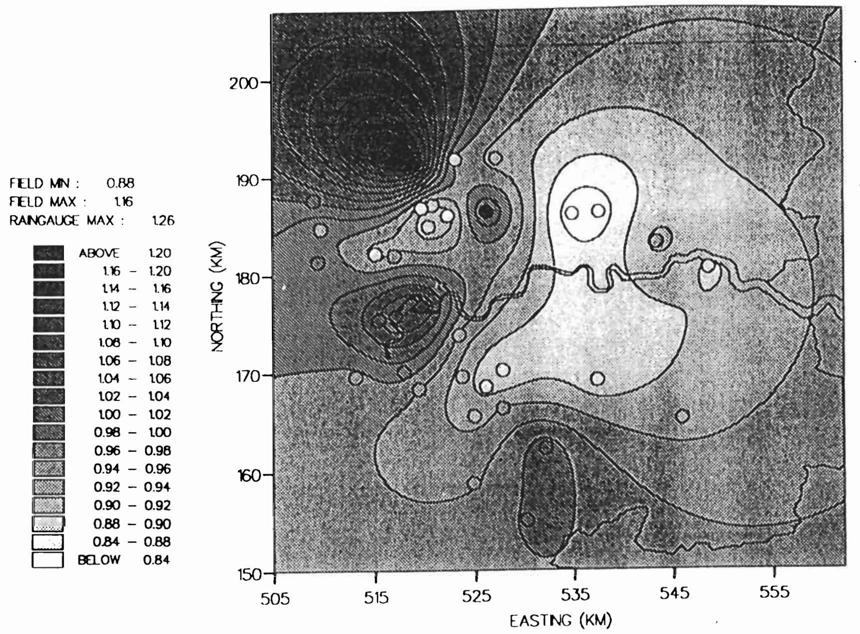


Figure 5.3.2b ***Mapping of storm duration distribution parameters: Lognormal distribution***

Location parameter, a



Scale parameter, b

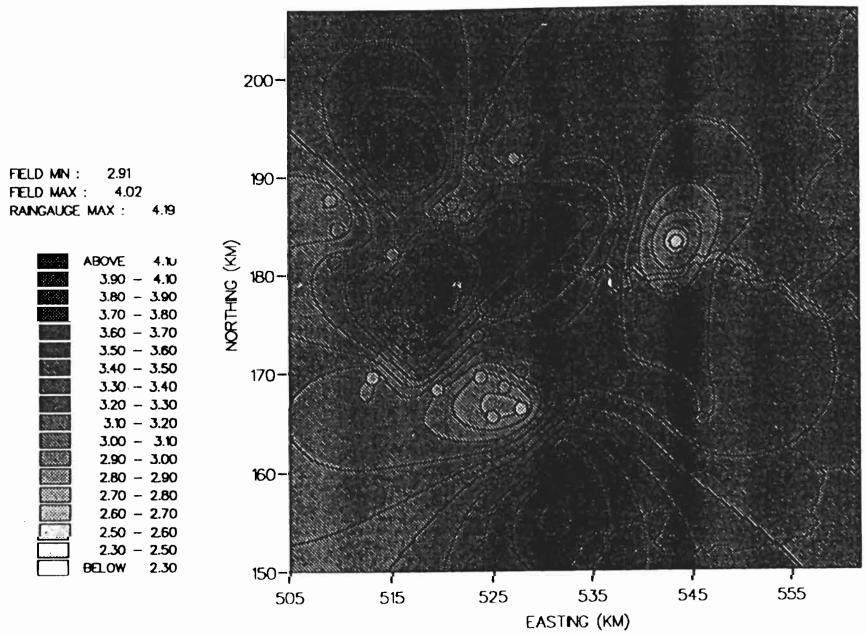
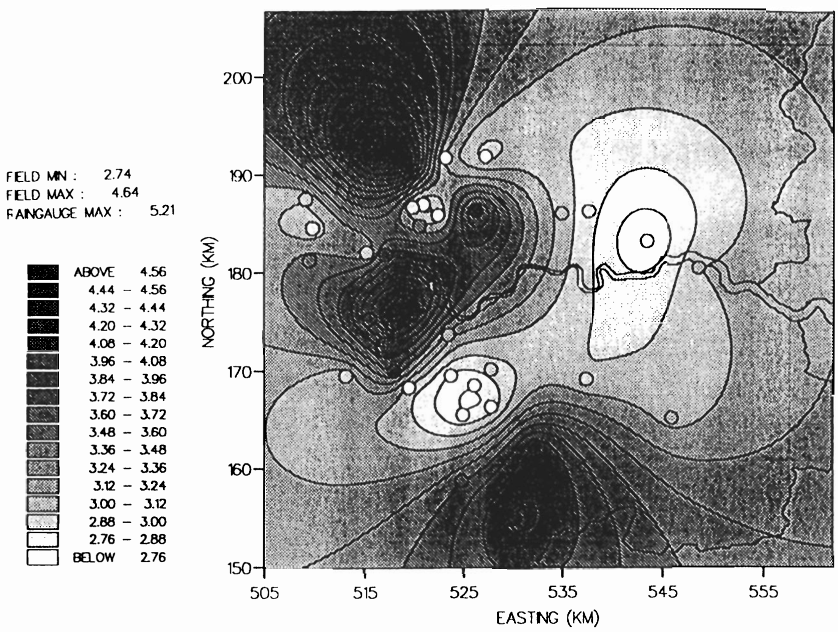


Figure 5.3.2c ***Mapping of storm duration distribution parameters: Gamma distribution***

Mean, ab



Standard deviation, $a^{1/2}b$

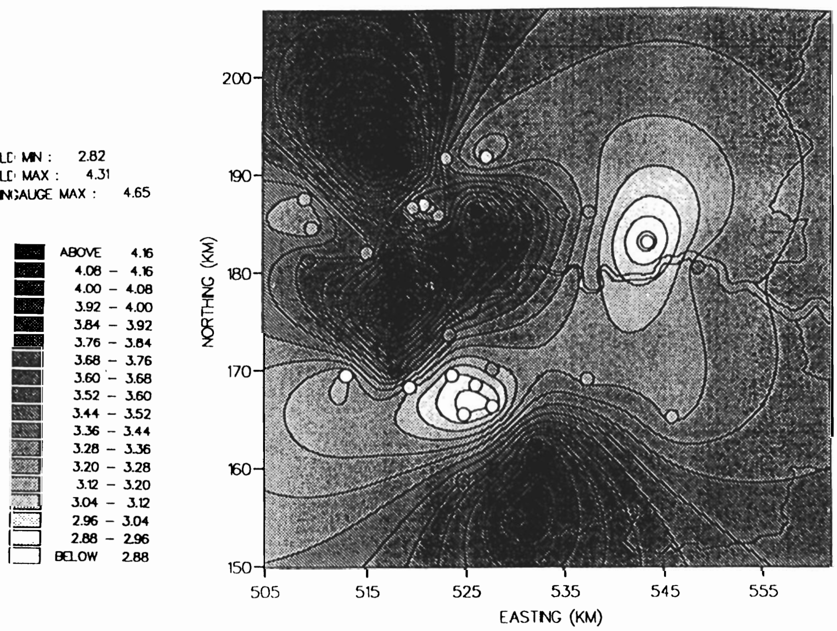
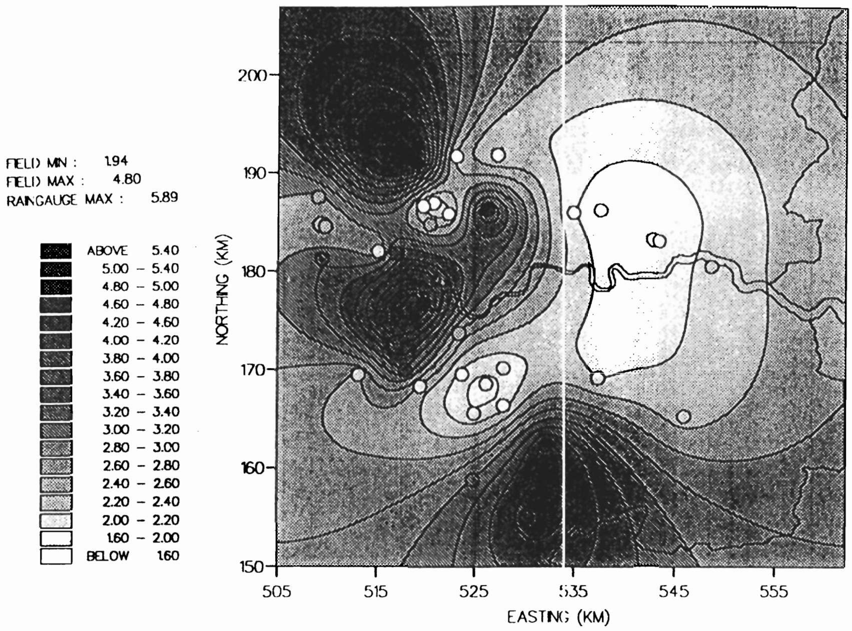


Figure 5.3.2d ***Mapping of storm duration distribution parameters: Gamma distribution***

Parameter a



Parameter k

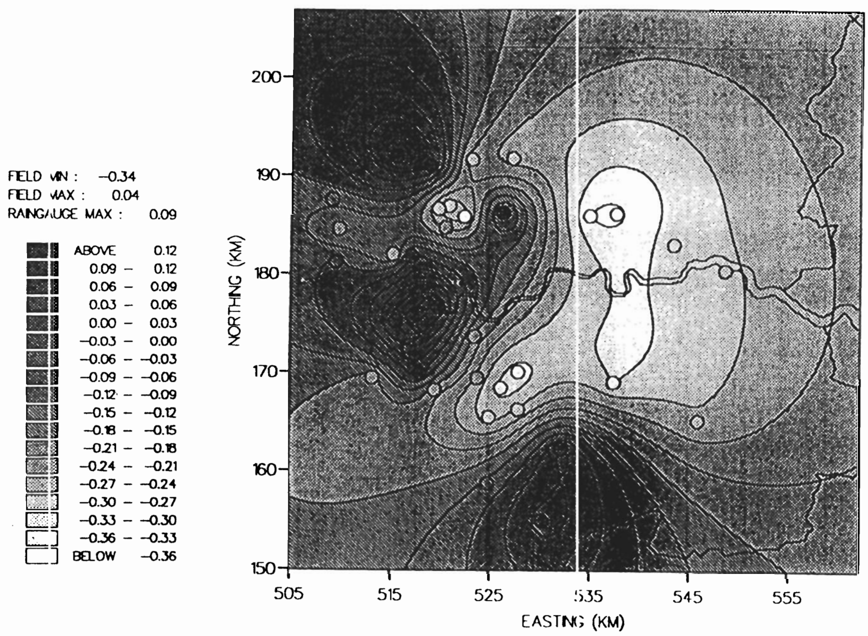


Figure 5.3.2e ***Mapping of storm duration distribution parameters: Generalised Pareto distribution***

Mean, a/(k+1)

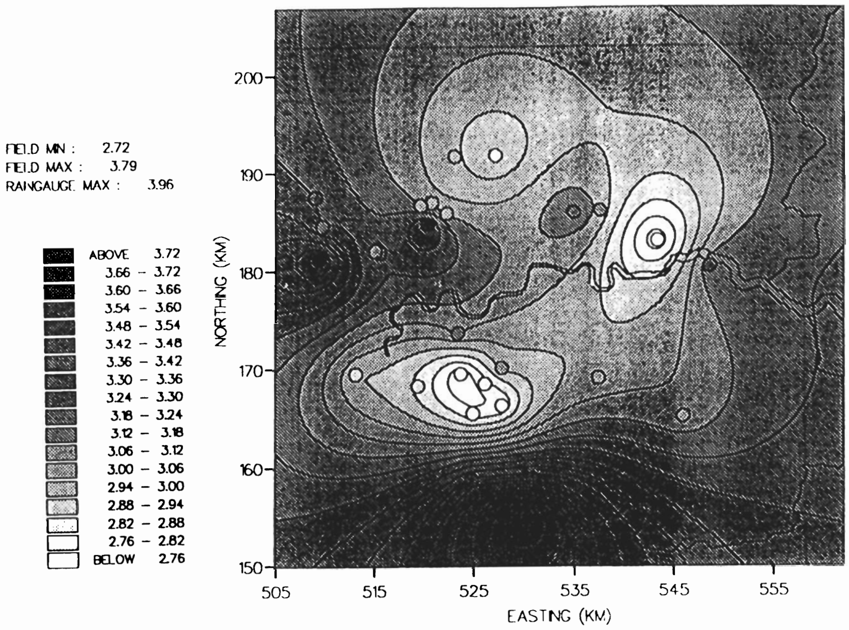


Figure 5.3.2f ***Mapping of storm duration distribution parameters: Generalised Pareto distribution***

very similar to those for other distributions. The parameter k has a small positive value for five gauges which means that in these cases a maximum possible duration is implied, equal to a/k.

5.4 DISTRIBUTION OF STORM PROFILES

Up to now consideration has been given only to the distribution of the duration and magnitude of the storm and not to the form of the profile of rainfall within a wet period. The analysis of storm profiles required special consideration. First the set of profiles were subdivided into sets of different duration: 4, 8, 12 and 16 hours. Since these displayed great variability the profiles for a given duration were averaged to form a smooth profile. These average profiles were plotted as cumulative rainfall over the duration of the storm. At each hour the cumulative rainfall was expressed as a proportion of the storm total so that the graph was standardised to a range of 0 to 1; similarly the time axis was standardised to the same range by expressing time from the start of the storm as a proportion of the storm duration.

A beta distribution has been fitted to the resulting average standardised storm profiles by the method of moments. The beta distribution function is defined as

$$F(t) = \int_0^t u^{a-1} \frac{(1-u)^{b-1}\, du}{B(a,b)},$$

with shape parameters a and b. The corresponding probability density function is

$$f(t) = \frac{t^{a-1}(1-t)^{b-1}}{B(a,b)} \tag{5.4.1}$$

where B(a,b) is the beta function

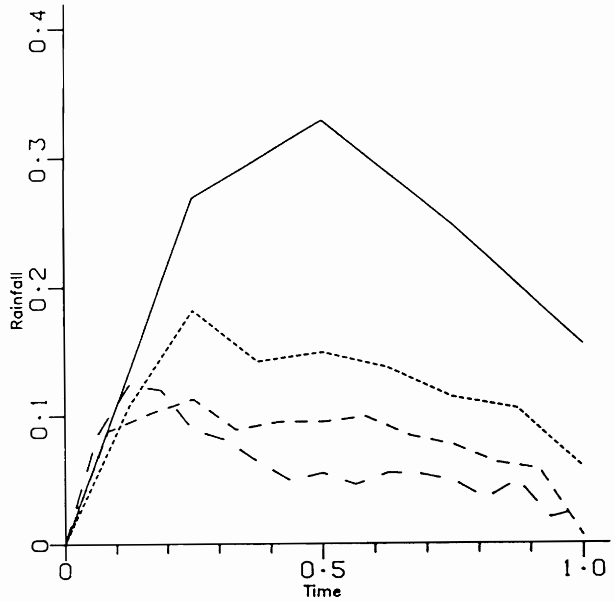
$$B(a,b) = \int_0^1 u^{a-1}\,(1-u)^{b-1}\, du. \tag{5.4.2}$$

Figures 5.4.1a and b presents average, standardized, rainfall profiles for different durations for Hayes and Hampstead, during summer and winter periods. These profiles suggest:

(i) shorter duration storms have the most symmetric profiles; and
(ii) longer duration profiles tend to rise rapidly and drop off more gradually.

Figures 5.4.1.c and d display the above profiles in standardized, cumulative form. Generally they are very similar across all durations, except that profiles for 16 hour durations tend to differ slightly from the rest.

Hampstead



Hayes

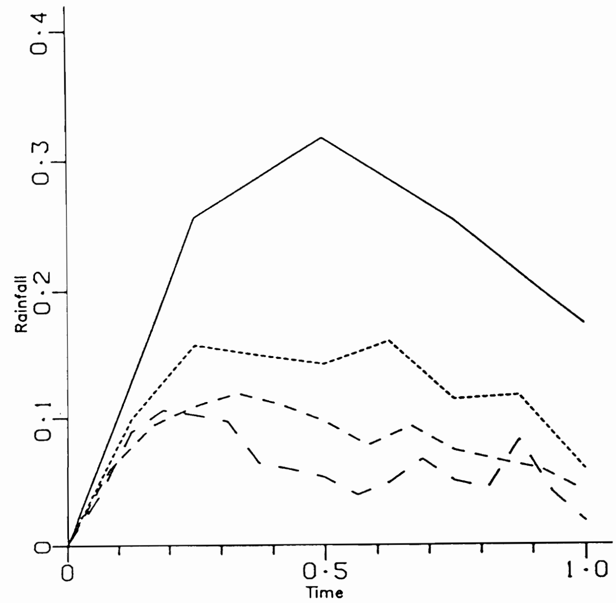
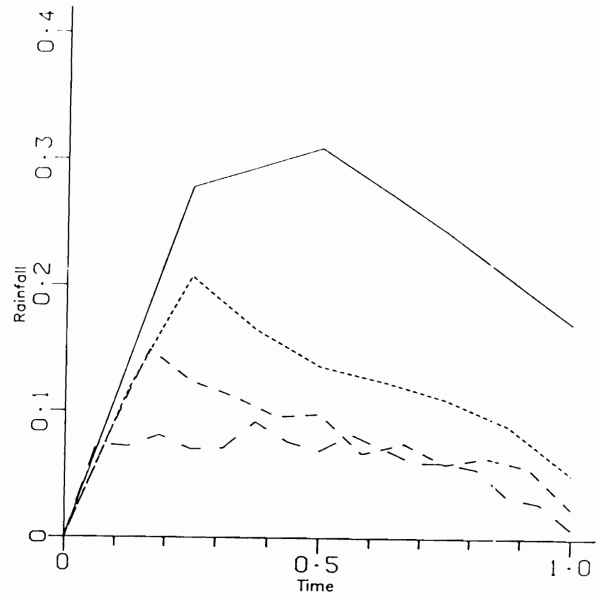


Figure 5.4.1.a ***Average standardized rainfall profiles for different durations: Winter (continuous line: 4 hours; short dashes: 8 hours; medium dashes: 12 hours; long dashes: 16 hours).***

Hampstead



Hayes

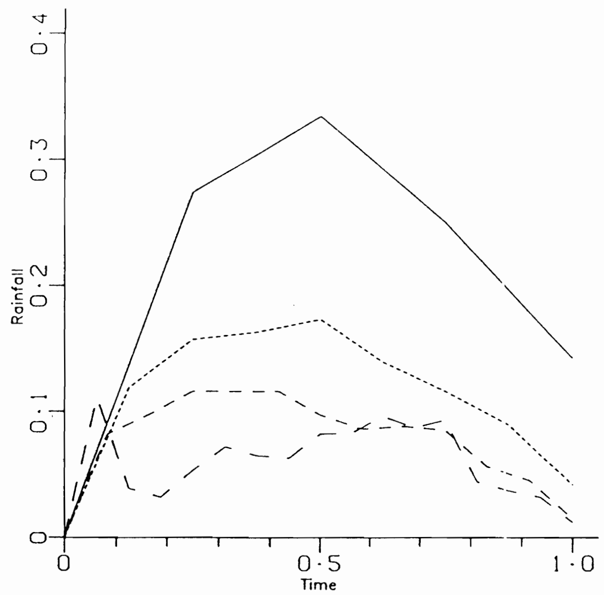
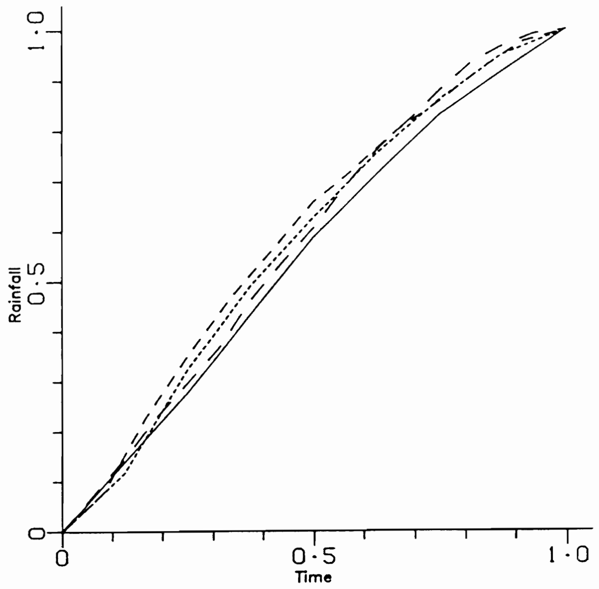


Figure 5.4.1.b ***Average standardized rainfall profiles for different durations: Summer (continuous line: 4 hours; short dashes: 8 hours; medium dashes: 12 hours; long dashes: 16 hours).***

Hampstead



Hayes

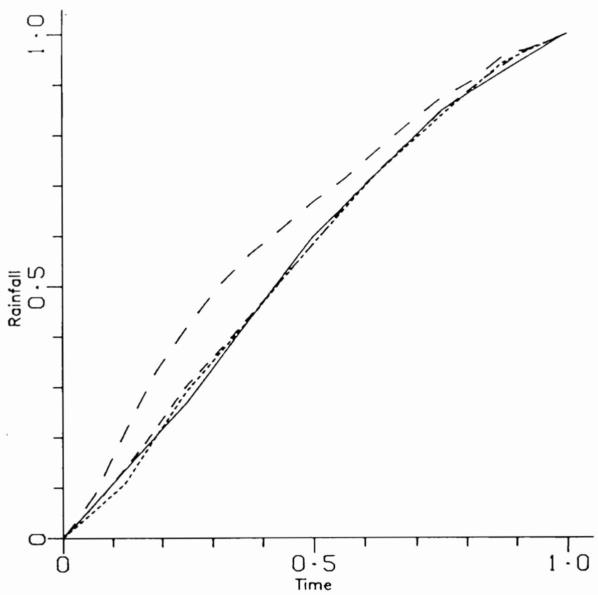
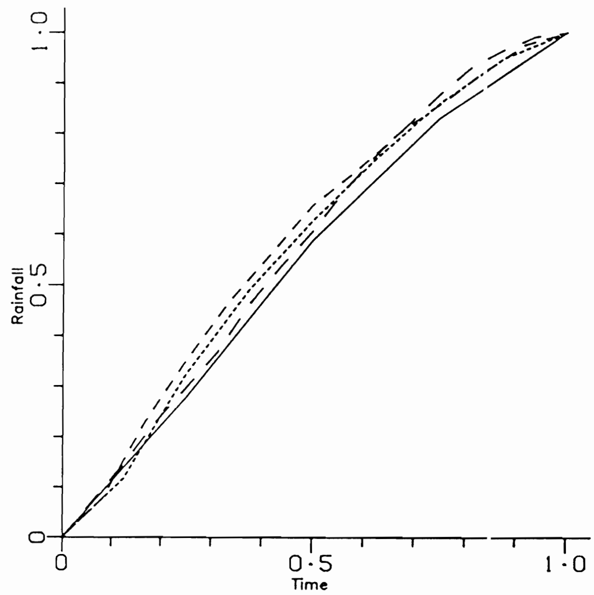


Figure 5.4.1.c ***Average standardized rainfall profiles in cumulative form for different durations: Winter (continuous line: 4 hours; short dashes: 8 hours; medium dashes: 12 hours; long dashes: 16 hours).***

Hampstead



Hayes

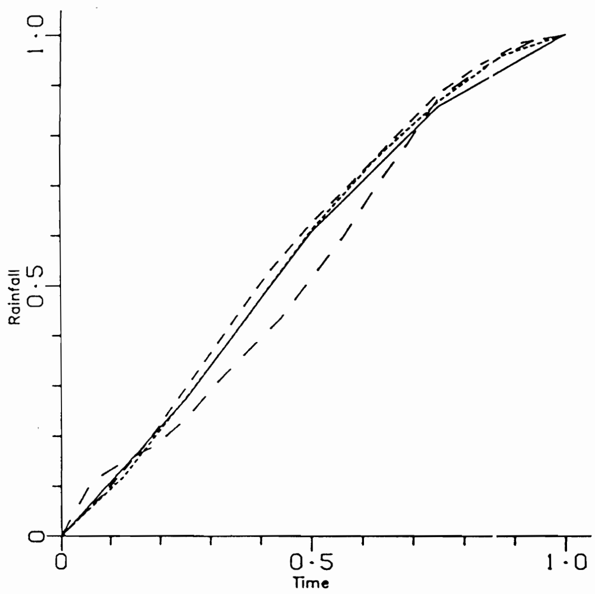


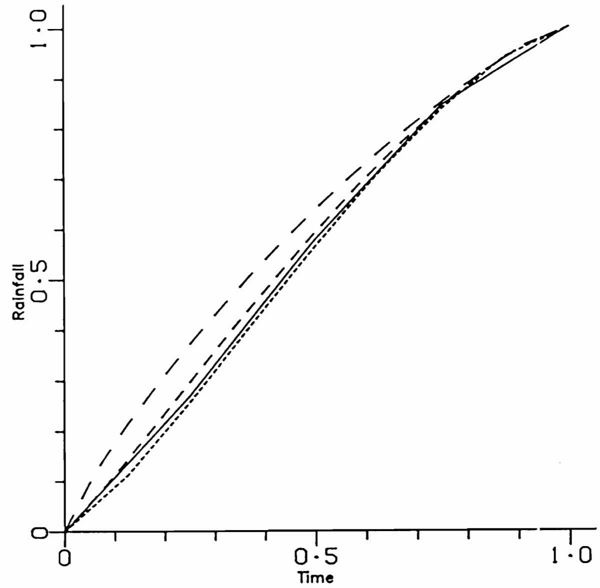
Figure 5.4.1.d ***Average standardized rainfall profiles in cumulative form for different durations: Summer (continuous line: 4 hours; short dashes: 8 hours; medium dashes: 12 hours; long dashes: 16 hours).***

Figures 5.4.2.a-d show the beta distributions which have been fitted to cumulative rainfall profiles for Hayes and Hampstead during the summer and winter periods.

5.5 CORRELATION ANALYSIS OF WITHIN-STORM TOTALS

A further way of describing the variability of hourly rainfalls within a storm event is through a correlation matrix showing the dependence of hourly rainfalls at different temporal lags. Table 5.5 shows the correlation matrix calculated from all storms of 12 hour duration for Hayes and Hampstead: correlations at lags 0, 1, through to 12 are presented. The correlation at lag 1 can be particularly dominant.

(a) Hayes



(b) Hampstead

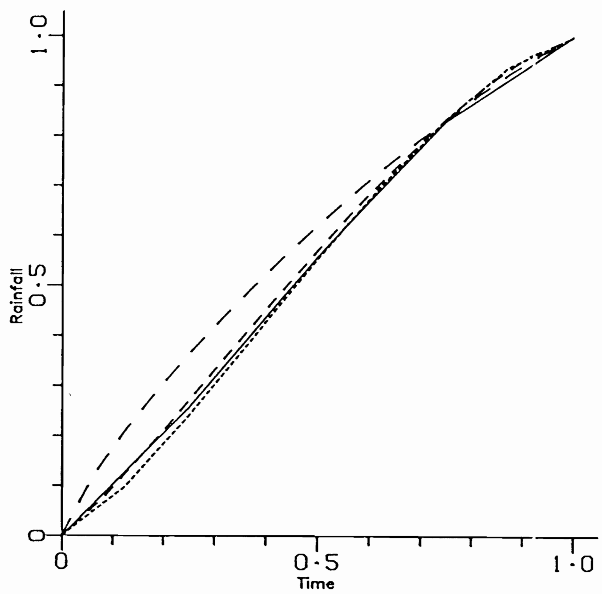
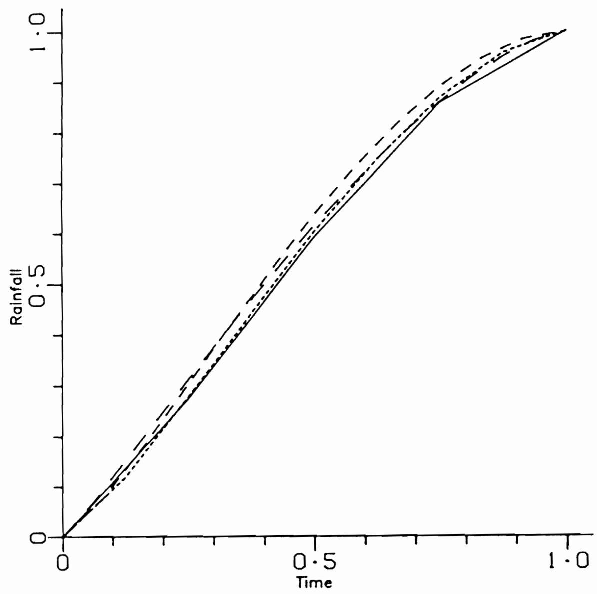


Figure 5.4.2 ***Beta distributions fitted to cumulative rainfall profiles: Winter***

(c) Hayes



(d) Hampstead

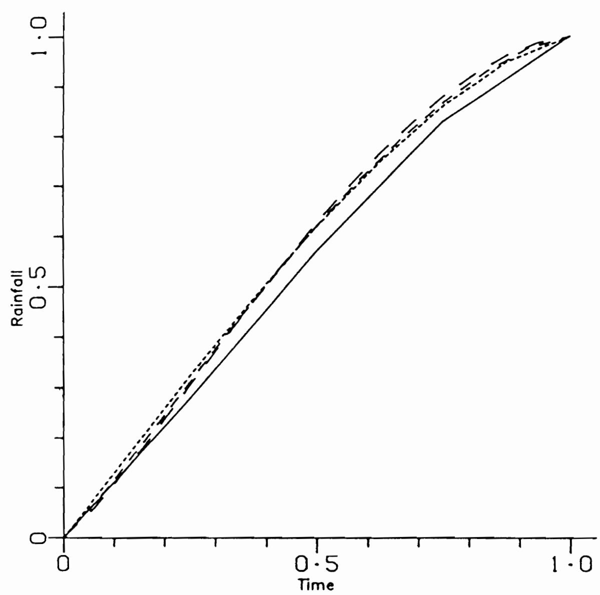


Figure 5.4.2 ***Beta distributions fitted to cumulative rainfall profiles: Summer***

Table 5.5 Correlation matrices calculated from all storms of 12 hour duration

(a) Hampstead

	Lag, hours										
	1	2	3	4	5	6	7	8	9	10	11
1.000	0.155	0.070	0.181	0.132	-0.021	-0.003	-0.023	-0.047	-0.084	-0.025	0.003
1.000	0.551	0.432	0.241	0.172	0.032	0.096	-0.004	0.123	0.116	0.081	
1.000	0.541	0.276	0.298	0.100	0.208	0.024	0.063	0.077	-0.016		
1.000	0.505	0.234	0.185	0.287	0.095	0.068	0.099	-0.025			
1.000	0.498	0.301	0.169	0.108	0.134	0.228	0.059				
1.000	0.466	0.357	0.142	0.058	0.163	0.011					
1.000	0.526	0.247	0.165	0.228	0.078						
1.000	0.425	0.279	0.169	0.071							
1.000	0.365	0.132	0.019								
1.000	0.616	0.134									
1.000	0.179										

(b) Hayes

	Lag, hours										
	1	2	3	4	5	6	7	8	9	10	11
1.000	0.258	0.259	0.043	0.431	0.077	-0.002	0.027	0.255	-0.030	-0.036	-0.095
1.000	0.456	0.137	0.201	0.049	0.059	0.098	0.153	-0.003	-0.024	-0.157	
1.000	0.338	0.152	0.100	0.242	0.175	0.369	0.182	-0.025	-0.124		
1.000	0.398	0.230	0.093	0.055	0.165	0.025	-0.056	-0.091			
1.000	0.451	0.199	0.196	0.298	-0.043	0.138	-0.108				
1.000	0.573	0.400	0.253	-0.004	0.141	-0.053					
1.000	0.747	0.451	0.195	0.069	0.057						
1.000	0.492	0.359	0.182	0.185							
1.000	0.511	0.108	0.094								
1.000	0.499	0.417									
1.000	0.579										

6. Depth-Duration-Frequency Analysis

6.1 INTRODUCTION

Knowledge of the frequency of occurrence of storms of a given depth and duration is fundamental to most storm drainage design studies. Additional information on how the frequency changes from point to point is clearly critical in designs requiring interpolation to an ungauged location. The derivation of depth-duration-frequency curves, or DDFs, using the PEPR data set is the concern of this Section.

Note that this form of analysis will be affected by missing values (see Section 3.3), but the effect has been suppressed by imposing the condition that only years for which at least 75% of the data are present can be used.

Previous sections have discussed maps which were produced showing the spatial variability over London of parameters of distributions describing storm depth, duration and profile inferred from fitting each distribution to each raingauge record. Note that since this form of analysis simply characterises the storm and not the frequency of occurrence it is not strongly affected by the missing value problem. The main thrust of this Section is to infer the rainfall intensity of a given duration and return period at each site and then to use an interpolation procedure to map this quantity continuously over the London area.

6.2 ISOHYETAL MAPS FOR A GIVEN DURATION AND RETURN PERIOD

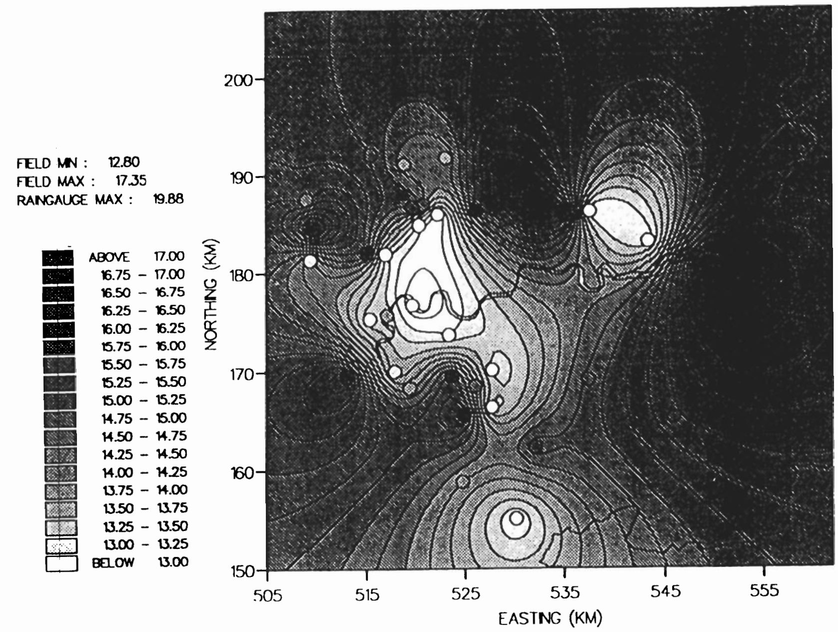
The procedure adopted to derive isohyetal maps of a given duration and return period involved first fitting Generalised Extreme Value (GEV) distributions by probability weighted moments to data from 35 gauges which had at least 5 years of record. The gauges were chosen by adding up all the days with data present for each gauge. Those gauges with at least an equivalent of 5 years worth of data were used. This is a much more stringent condition than that used in Section 3. (Note that the number of years used in this method falls below 5 for one gauge because of the above condition that 75% of the data must be there for a year to be used).

At each site the fitted GEV distribution was used to infer the rainfall depth of a given duration and return period. The multiquadric surface fitting method was used to interpolate between gauge points in order to draw the required isohyetal map for the chosen duration and return period. Figure 6.2.1 shows maps of rainfall depths obtained for various durations and return period storms. It is difficult to pick out a consistent overall pattern from this figure between various durations and return periods. Figure 6.2.2 is a graph of these average depths against log-return period for all durations. Note that the presence of only five years of record at some sites makes inferences to return periods of 20 years or more of dubious value. The 1 hr 5 year return period is most often used as the basis of urban storm sewer design and results for this case deserve closer scrutiny.

6.3 DEPTH-DURATION-FREQUENCY CURVES FOR HAYES AND HAMPSTEAD

Whilst the previous Section has focussed on mapping the rainfall corresponding to a given duration and return period it is of interest to display actual DDF's derived for particular gauges. Figure 6.3.1 shows the results obtained for Hayes and Hampstead; as before inferences for higher return periods should be interpreted cautiously in the light of the length of record on which they are based.

(a) 1 hour duration, 5 year return period



(b) 1 hour duration, 20 year return period

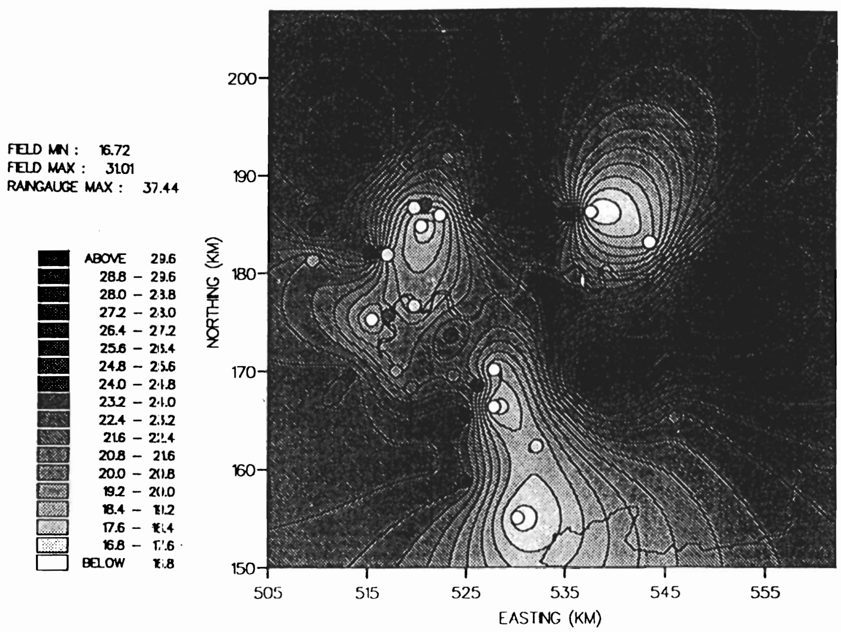
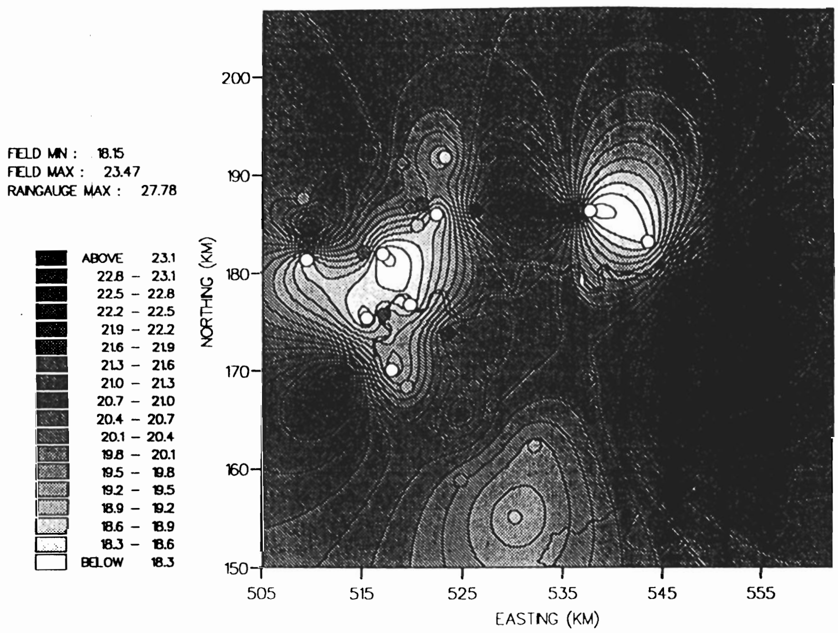


Figure 6.2.1 *Map of rainfall depths over London for a given duration and return period*

(c) 2 hour duration, 5 year return period



(d) 2 hour duration, 20 year return period

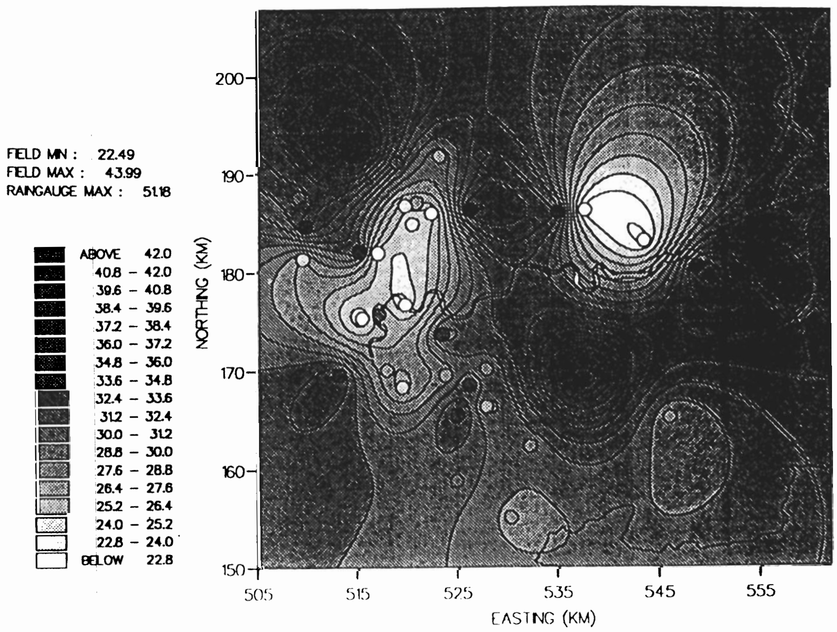
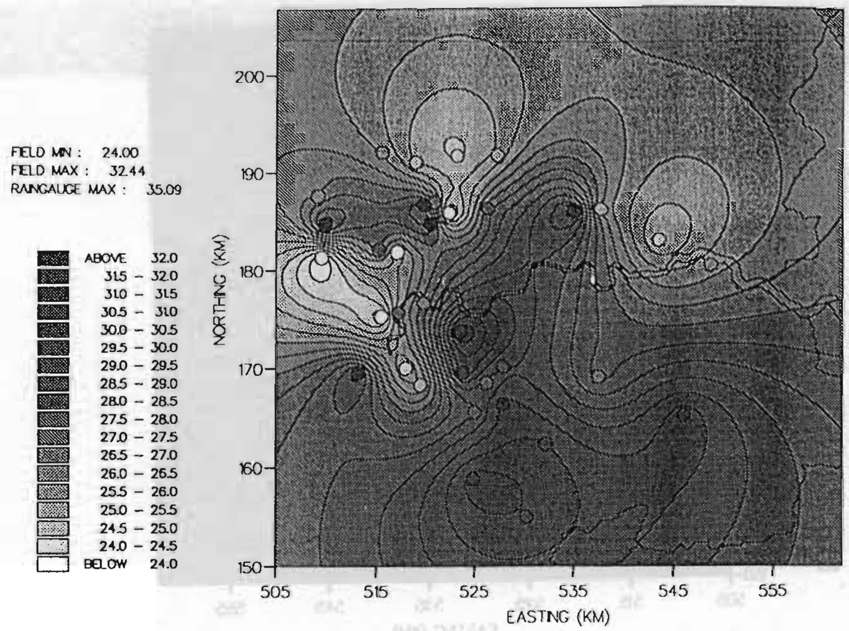


Figure 6.2.1 continued ***Map of rainfall depths over London for a given duration and return period***

(e)   4 hour duration, 5 year return period



(f)   4 hour duration, 20 year return period

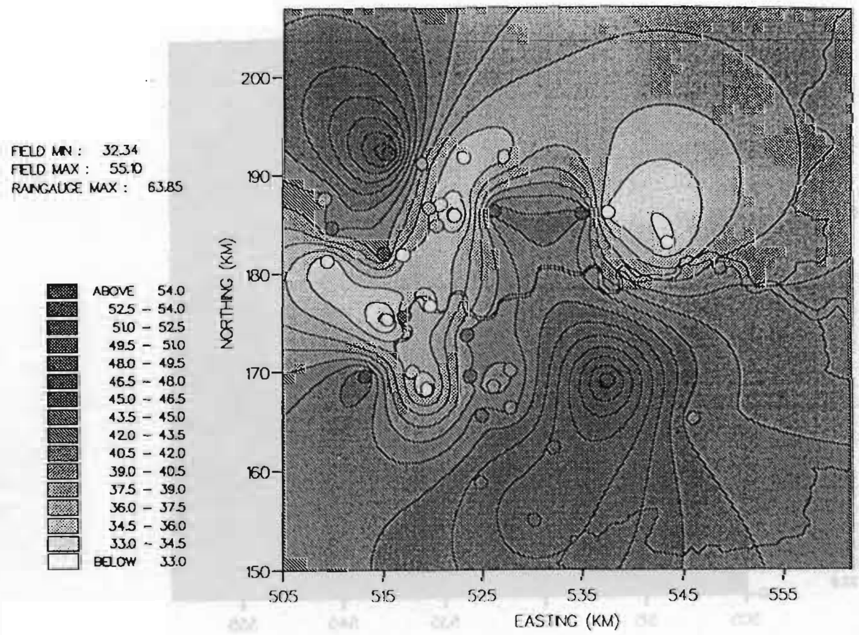
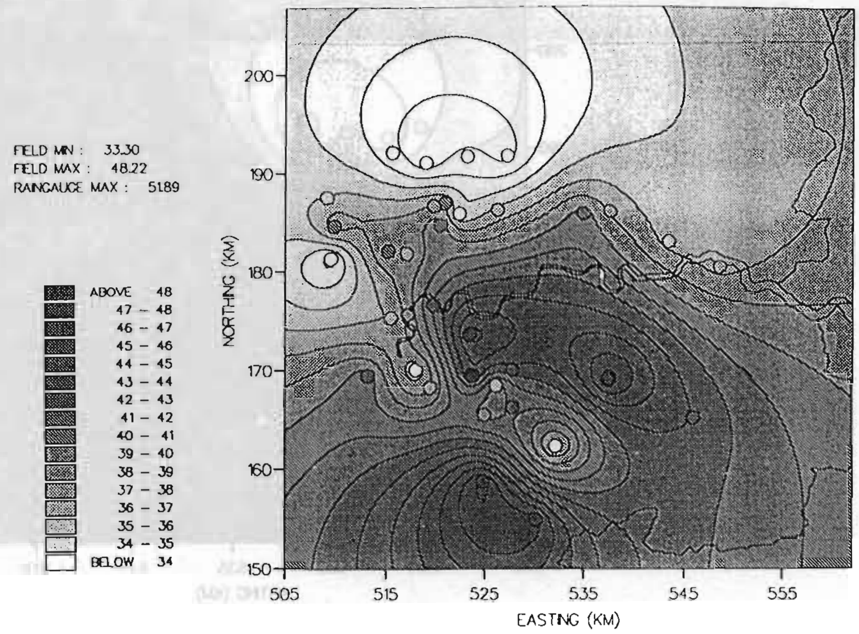


Figure 6.2.1 continued   Map of rainfall depths over London for a given duration and return period

(g) 12 hour duration, 5 year return period



(h) 12 hour duration, 20 year return period

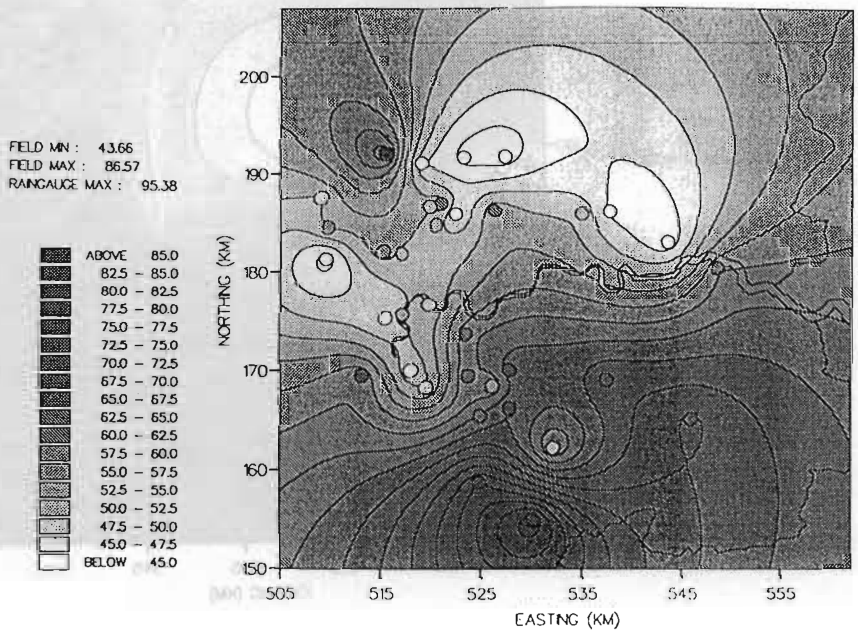
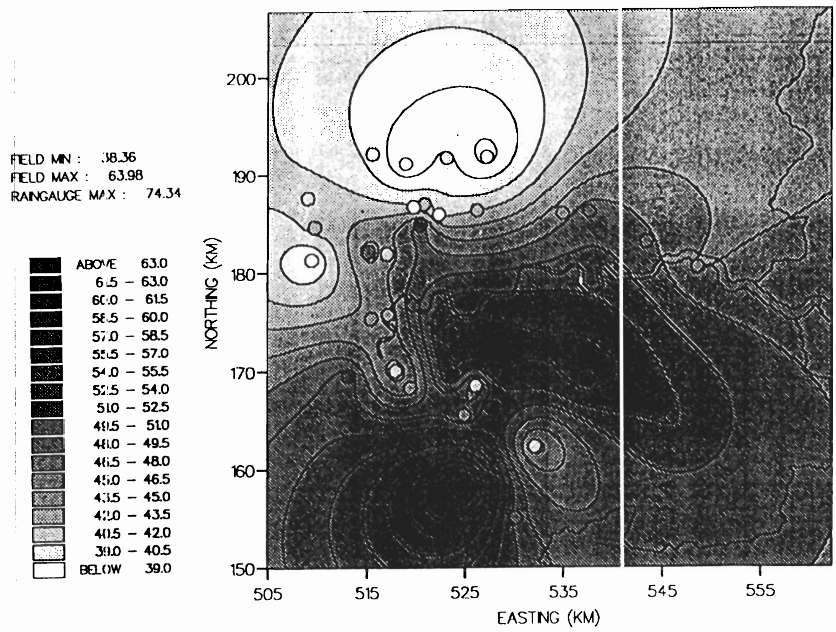


Figure 6.2.1 continued ***Map of rainfall depths over London for a given duration and return period***

(i) ***24 hour duration, 5 year return period***



(j) ***24 hour duration, 20 year return period***

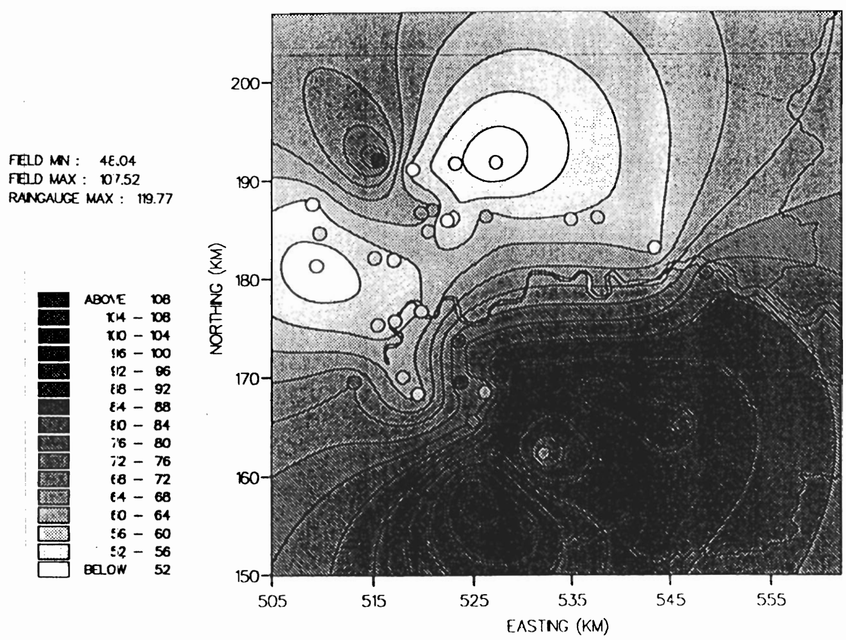


Figure 6.2.1 continued ***Map of rainfall depths over London for a given duration and return period***

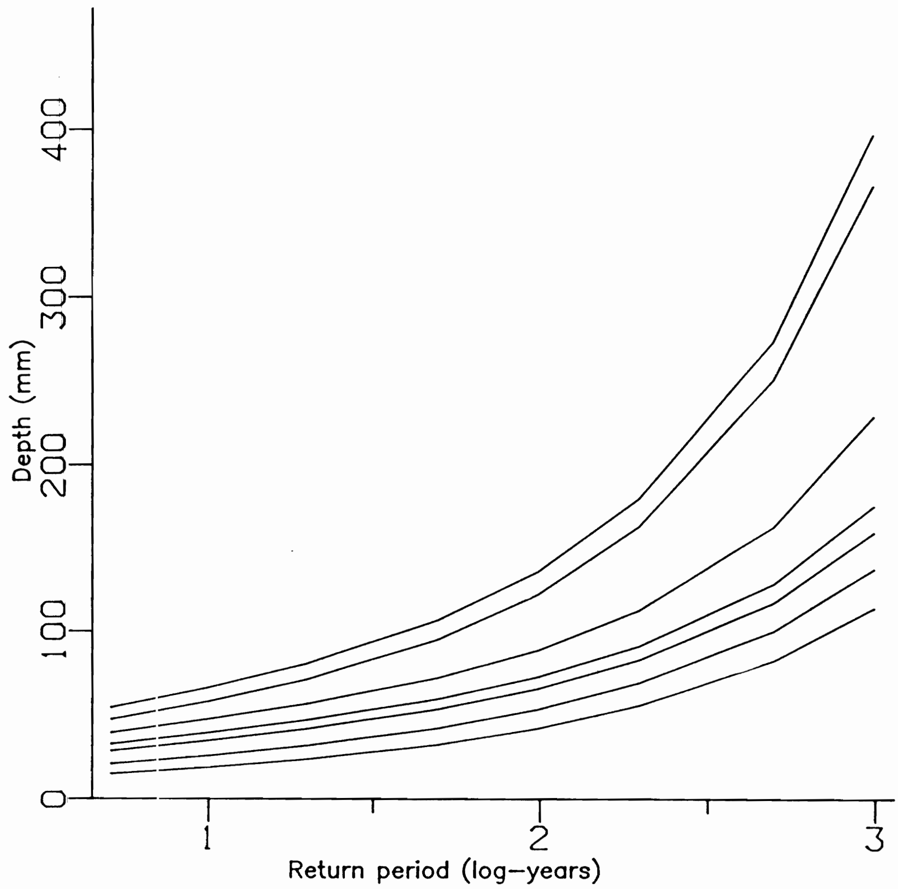
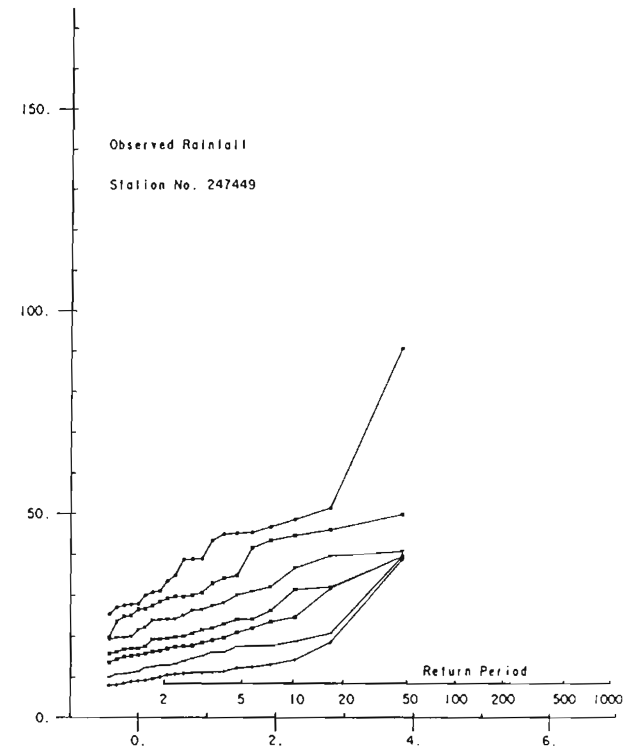


Figure 6.2.2 ***Depth-duration-frequency curves of rainfall depth in mm for durations of 1, 2, 4, 6, 12, 24 and 48 hours: average over 35 gauges.***

Hayes



Hampstead

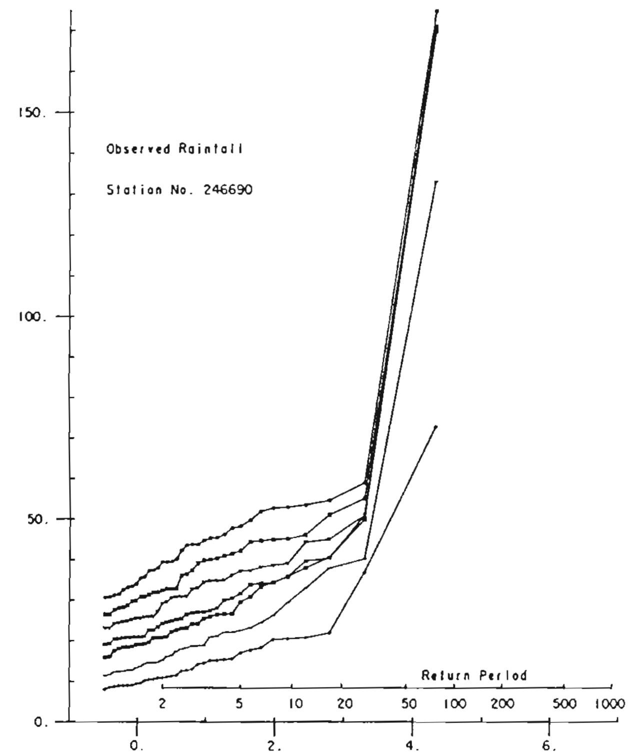


Figure 6.3.1 ***Depth-duration-frequency curves of rainfall depth in mm for durations of 1, 2, 4, 6, 12, 24 and 48 hours.***

7. Analysis of sub-hourly rainfall amounts

7.1 INTRODUCTION

An investigation of rainfall variability for intervals of less than one hour has focused on calculating the proportion of days that rainfall of a given depth and duration occurs. This has essentially included emulating the analysis carried out by Bilham in 1935 using the PEPR data set for London. The problems of extracting sub-hourly totals from the PEPR data set are described in the next subsection. This is followed by details of the daily counting procedure used, and then the results from an analysis of 30 raingauges. Sub-section 7.4 presents a detailed re-examination of the Bilham formula, as it applies to storms over London, in the light of the PEPR data set.

7.2 RETRIEVAL OF SUB-HOURLY RAINFALL TOTALS

The PEPR data are stored as multiple files with one file containing data for one month for one station. Rainfall data are held both as hourly rainfall depths and as a cumulative amount within the day (where a day is from 9 am to 9 am) along with its associated time or recording: the time is recorded to one minute precision (but clock drift can greatly affect absolute timing accuracy).

In order to record the number of days containing a given depth-duration rainfall the rainfall depths and recording times have been stored in two arrays. Data for the whole of the month being retrieved are missing if the error flag for the month is not zero: in this case the depths in the array were set to missing and the time array set to the number of minutes in the month. Given that data are available for the month then the data are analysed a day at a time. If data are missing for the day then the depth array is set to a missing value and the time array set to the number of minutes in a day. If data are present then the cumulative rainfalls are examined first. For zero rainfall the depth array is set to zero and the time array set to the number of minutes in the day. In the case of rain then, if the cumulative rainfall is not reset, the differences in consecutive cumulative depths and associated times gives the depth and times to be placed in the respective arrays. In the event of a reset in the cumulative values the cumulative values are ignored and the hourly values used instead for that day and 60 minutes entered into each time array for that day. If an hourly value is missing then the depth is entered as missing and 60 minutes entered as the time. At the end of each day or at the end of a missing month data values of -1 are placed as markers in the depth and time arrays.

7.3 DAY COUNTS OF GIVEN DEPTH-DURATION RAINFALLS

Consideration has been given to rainfalls of the following nine durations in minutes: 6, 15, 30, 60, 120, 240, 360, 720 and 1440. Three rainfall depths in mm have been considered: 5, 10 and 25. These were chosen to allow a direct comparison to be made with the classic analysis of heavy rainfalls of short duration carried out by Bilham reported in British Rainfall, 1935.

For each combination of depth and duration a count is made of the days on which a given depth-duration occurs. Days may be counted in two ways:

(a) By checking whether the values in the depth and time arrays comply with the depth-duration required. Note that only one successful count is allowed per day.

(b) By adding together consecutive depths and times and checking that their sums comply with the depth-duration required. Again only one successful count per day is allowed.

The following points should be noted concerning the counting operation:

(i) Note that a "fall" need not be continuous but that the duration must include durations of any intervening dry periods. It is clearly important to record time intervals associated with periods of missing data.

(ii) A fall need not be confined to one calendar day, but no portion of the record should be used twice for depth-durations on consecutive days. Therefore, if two days are covered, the data which fall on the day not counted cannot be used in any way to count for that day. This requires that a record be kept of the start and finish times. The day which is counted is that with the greater portion of the rainfall; if exactly the same rainfall occurs in both days then the day with the larger proportion of the duration is counted.

(iii) Whilst a day can only count once for one depth-duration it can be counted again for other depth-durations.

Having performed counts for all depth-durations then the number of days per year for each depth-duration combination is calculated.

To account for any missing days a count is made of all days when data are present over the analysis period. This is then converted into years and the total number of days counted is divided by this figure.

Only gauges with at least 5 years worth of data were used in the analysis. These were identified by counting the total number of days for which data are available for each gauge. Those gauges with at least 5 years worth of data are presented in Table 7.3.1.

Since 'dry' months were included in this count the actual amount of reliable data was lower for some gauges. Section 6 of Appendix A contains a list of gauges with their corresponding 'dry' months. In the analyses which follow only years free of these 'dry' months are used. The number of gauges which have at least 5 years worth of data free from these suspect months is 30.

Table 7.3.1 Gauges with at least 5 years of data

Station number	Station name	Number of years when days present are counted
239551	Folkstone Road	6.27
244990	Muswell Hill	7.91
245310	Clapton Pond	15.27
245345	Auckland Road	5.05
246627	Mill Hill	15.34
246690	Hampstead	39.79
246719	Stanmore	26.00
246738	Chandos Rec. Gd.	28.97
246847	Brent Reservoir	24.61
246956	Wembly	5.09
246979	Gladstone Park	5.91
247003	Stonebridge Park	7.93
247060	Ealing Castlebar	12.92
247077	Brentside School	9.19
247344	Northolt Aerodrome	26.13
247449	Hayes, Wood End Ns.	26.52
247669	Mogden STW	7.90
279502	Ruislip	19.08
284152	Hampton	20.91
286392	Hogsmill STW	17.38
286405	Canbury Gardens	25.36
287049	Kew Observatory	30.03
287059	Kew STW	9.97
287144	Sutton STW	34.16
287203	Raynes Park PS	12.42
287283	Putney Heath	9.34
287426	Banstead	7.02
287520	Alderstead Heath	5.32
287722	Purley Oaks	7.13
287883	Carshalton PS	5.73
287909	Morden Hall	14.58
287946	London Road	10.38
288749	Kelsey STW	6.69
290007	Crossnes STW	8.51
291241	Orpington	8.11

Table 7.3.2 depicts the number of days per year, n, where at least 5, 10 or 25 mm fell within a given time for the 30 raingauges. The mean and standard deviation for each depth and duration are also given. Figure 7.3.1 presents plots of 5, 10 and

25 mm for Hayes, Hampstead and when averaged over all 30 raingauges. Figure 7.3.2 presents maps of n for various depths and time limits.

A revised Bilham formula is given in 'Appendix to Hydrological Memoranda No 33' (UK Met. Office, 1968). It can be written as

$$n' = 1.39t\ (r' + 0.1)^{-3.55} \tag{7.3.1}$$

where n' is the number of days counted in 10 years, t is the time in hours and r' the rainfall in inches. Using n=n'/10 the values of n found from this formula have been compared with the mean count given in Table 7.3.2. These are shown in Figure 7.3.3 for depths of 5, 10 and 25 mm. Figure 7.3.4 is similar except that log n against log t is plotted instead. The durations that Bilham originally looked at were 6, 15, 30, 60 minutes for 5 mm; 15, 30, 60, 120 minutes for 10 mm and 1, 2, 5, 24 hours for 25 mm. For each depth it can be seen that there is good correspondence between the n obtained using the PEPR data set and the value of n found using equation (7.3.1), within these time intervals. Outside these limits however there is greater discrepency. For a 5 mm depth there is good correspondence up to about 100 minutes, for a 10 mm depth, good correspondence up to about 360 minutes and for a 25 mm depth the correspondence is good after about 20 minutes.

The Met. Office Appendix also gives a replacement of Bilham's formula for intensities greater than 1.25 inches/hr (~32 mm/hr), which is given by

$$n' = r'\ \exp\ (1-0.8r't^{-1})(r' + 0.1)^{-3.55}. \tag{7.3.2}$$

In Table 7.3.3 the mean of n obtained from the PEPR data set is compared to the n found from equations (7.3.1) and (7.3.2) with n=n'/10.

The mean values of n' which Bilham obtained from observations over England and Wales are compared in Table 7.3.4 with n' found using the PEPR data set. There is fairly good correspondence for the durations considered. The following sub-section examines this correspondence in more detail, first reviewing the background to the various Bilham-type relations, and then developing a new composite relation based on the PEPR dataset.

Table 7.3.2a *Number of days per year where at least 5 mm fell within a given time for 30 raingauges over London*

	Time (minutes)									
Gauge	6	15	30	60	120	180	360	720	1440	Years
Folkstone Road	0.48	1.75	3.19	7.49	14.66	24.23	28.53	34.27	40.96	6.27
Muswell Hill	1.14	3.03	4.30	8.09	16.69	28.07	33.76	40.58	51.46	7.91
Clapton Pond	1.51	3.95	6.16	10.93	17.79	27.44	32.21	38.60	48.02	8.6
Auckland Road	0.40	1.19	3.37	7.72	15.05	23.37	27.13	32.48	40.01	5.05
Mill Hill	0.17	0.17	3.44	7.40	16.17	24.77	29.58	36.81	44.03	5.81
Hampstead	0.77	2.36	4.77	9.46	18.19	29.18	34.62	42.10	51.35	39.03
Stanmore	0.57	2.05	4.67	9.13	17.69	28.04	33.97	41.62	49.13	22.90
Chandos Rc. Gd.	1.06	2.91	5.21	9.53	18.62	29.56	35.11	42.17	51.44	11.33
Brent Reservoir	0.45	2.57	4.53	9.06	18.39	29.40	35.21	42.59	51.93	17.89
Wembley	1.57	2.56	5.11	10.42	18.09	28.71	35.00	40.51	49.16	5.09
Gladstone Park	0.00	0.51	0.51	2.71	7.45	11.35	14.90	18.29	24.05	5.91
Stonebridge Park	0.38	2.27	3.78	9.21	15.64	25.60	30.90	36.57	44.27	7.93
Ealing Castlebar	0.58	1.99	3.82	10.13	16.44	27.24	32.89	40.53	49.33	12.04
Brentside School	0.33	1.41	2.39	7.29	13.82	25.57	31.22	38.62	47.43	9.19
Northolt Aero.	0.73	2.48	4.92	9.40	17.94	28.84	34.37	41.61	52.82	24.58
Hayes	0.78	1.92	4.14	7.93	15.94	25.75	30.36	38.30	46.11	25.59
Mogden	0.13	1.65	2.78	6.08	14.81	23.29	28.60	36.07	43.54	7.90
Ruislip	0.52	2.31	4.46	9.75	17.98	28.67	35.17	42.83	52.68	19.08
Hampton	0.62	2.30	3.78	8.80	15.88	27.50	32.81	39.89	50.61	20.91
Hogsmill	0.63	1.96	4.09	9.21	17.60	28.77	33.54	40.67	49.88	17.38
Canbury Gdns.	0.80	1.79	3.30	7.14	12.50	20.35	24.55	31.69	39.63	11.20
Kew Obs.	0.53	2.07	4.06	8.93	16.99	26.14	31.71	38.53	47.63	30.03
Kew Stw	0.40	1.61	3.21	7.83	15.35	24.08	28.69	35.01	41.23	9.97
Sutton Stw	0.54	1.60	3.55	7.89	16.08	25.50	30.53	37.43	45.53	33.21
Raynes Pk Ps	0.52	2.16	4.14	7.76	14.75	23.81	28.73	35.37	43.05	11.59
Putney Heath	0.67	3.33	4.49	7.98	13.63	20.12	23.61	30.26	37.25	6.01
Banstead	0.57	2.71	5.42	11.12	23.52	36.63	43.33	51.59	62.00	7.02
Alderstead Heath	0.19	0.75	1.88	6.39	13.34	21.79	30.24	37.75	43.95	5.32
Crossness Stw	0.60	1.32	3.23	6.46	14.11	22.71	28.09	33.23	40.29	8.37
Orpington	0.55	2.58	4.60	8.28	16.37	25.76	31.27	36.06	42.86	5.44
Mean	0.61	2.04	3.91	8.32	16.05	25.74	31.09	37.73	46.02	
s.d	0.35	0.80	1.12	1.67	2.68	4.27	4.89	5.57	6.66	

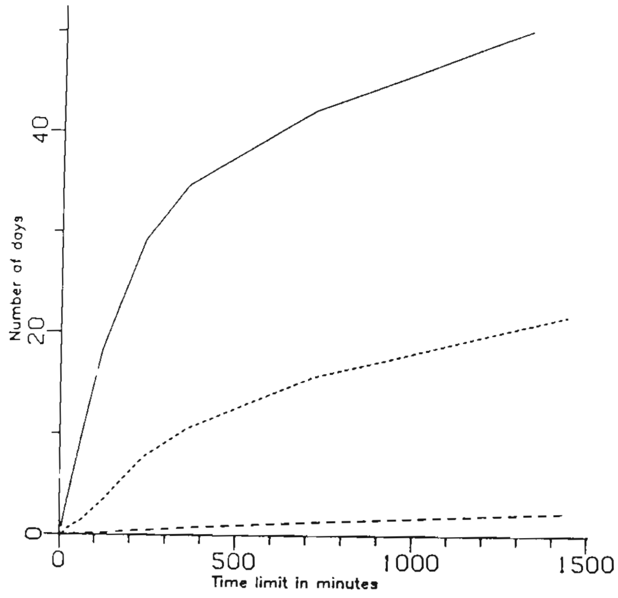
Table 7.3.2b ***Number of days per year where at least 10 mm fell within a given time for 30 raingauges over London***

	Time (minutes)									
Gauge	6	15	30	60	120	180	360	720	1440	Years
Folkstone Road	0.00	0.64	0.80	1.43	2.87	6.54	9.24	12.59	17.37	6.27
Muswell Hill	0.13	0.38	1.01	2.02	3.16	6.45	9.36	12.90	18.96	7.91
Clapton Pond	0.12	0.81	1.16	2.33	3.84	6.74	9.54	12.67	19.07	8.60
Auckland Road	0.00	0.00	0.20	1.39	2.38	6.34	7.92	10.89	16.83	5.50
Mill Hill	0.00	0.17	0.52	0.86	2.24	6.71	9.63	15.65	19.26	5.81
Hampstead	0.00	0.36	0.79	1.36	3.28	7.74	10.51	15.66	21.65	39.03
Stanmore	0.04	0.26	0.61	1.31	3.28	7.34	9.96	14.02	20.18	22.90
Chandos Rc. Gd.	0.18	0.53	0.88	1.50	3.44	6.79	9.97	14.29	22.15	11.33
Brent Reservoir	0.00	0.11	0.56	1.17	2.96	6.65	9.67	14.37	21.24	17.89
Wembley	0.59	0.79	1.18	1.77	3.74	8.06	10.42	13.96	20.06	5.09
Gladstone Park	0.00	0.00	0.17	0.34	0.85	2.20	3.90	5.76	7.79	5.91
Stonebridge Park	0.00	0.00	0.38	1.26	3.28	6.68	8.83	12.49	17.15	7.93
Ealing Castlebar	0.08	0.08	0.33	1.16	3.16	6.98	9.63	14.70	19.93	12.04
Brentside School	0.00	0.21	0.54	0.98	1.74	4.90	6.96	11.53	17.08	9.19
Northolt Aero.	0.04	0.49	0.85	1.46	3.58	7.49	10.17	15.05	22.17	24.58
Hayes	0.12	0.39	0.55	1.29	2.62	6.37	8.52	12.15	17.58	25.59
Mogden	0.00	0.00	0.25	1.01	1.90	5.32	7.72	11.52	16.71	7.90
Ruislip	0.11	0.16	0.63	1.10	2.67	6.50	9.96	15.31	21.75	19.08
Hampton	0.05	0.43	0.86	1.24	3.21	6.55	8.51	13.30	19.56	20.91
Hogsmill	0.00	0.29	0.69	1.44	3.28	6.73	9.84	14.27	19.91	17.38
Canbury Gdns.	0.09	0.27	0.45	0.89	2.50	5.53	7.14	10.35	14.55	11.20
Kew Obs.	0.03	0.33	0.63	1.17	2.76	6.46	9.26	12.92	19.22	30.03
Kew Stw	0.00	0.10	0.60	1.30	2.41	5.32	8.13	11.74	16.65	9.97
Sutton Stw	0.03	0.27	0.63	1.39	2.86	6.41	9.33	13.73	19.12	33.21
Raynes Pk Ps	0.09	0.09	0.95	1.47	2.67	5.26	8.02	12.25	16.82	11.59
Putney Heath	0.17	0.17	0.50	1.83	3.49	5.32	7.32	9.98	13.80	6.01
Banstead	0.00	0.29	0.86	2.00	4.13	9.83	14.96	20.95	28.93	7.02
Alderstead Heath	0.00	0.19	0.19	0.75	1.07	5.45	7.89	12.77	19.35	5.32
Crossness Stw	0.12	0.48	0.84	1.20	2.27	5.62	7.89	10.88	14.23	8.37
Orpington	0.00	0.18	0.55	1.29	3.50	6.62	9.38	13.80	18.58	5.44
Mean	0.07	0.28	0.64	1.32	2.87	6.36	8.99	13.08	18.59	
s.d	0.11	0.22	0.27	0.40	0.70	1.26	1.77	2.51	3.55	

Table 7.3.2c ***Number of days per year where at least 25 mm fell within a given time for 30 raingauges over London***

	Time (minutes)									
Gauge	6	15	30	60	120	180	360	720	1440	Years
Folkstone Road	0.00	0.00	0.00	0.00	0.00	0.16	0.64	2.07	2.55	6.27
Muswell Hill	0.00	0.00	0.00	0.13	0.13	0.25	0.89	1.64	2.91	7.91
Clapton Pond	0.00	0.00	0.12	0.12	0.35	0.70	0.93	1.74	2.21	8.60
Auckland Road	0.00	0.00	0.00	0.00	0.00	0.40	0.59	1.39	1.78	5.05
Mill Hill	0.00	0.00	0.00	0.17	0.17	0.34	0.34	1.89	3.10	5.81
Hampstead	0.00	0.00	0.03	0.10	0.21	0.46	0.72	1.31	2.28	39.03
Stanmore	0.00	0.00	0.04	0.09	0.13	0.22	0.44	0.96	1.49	22.90
Chandos Rc. Gd.	0.00	0.00	0.09	0.18	0.27	0.44	0.44	0.97	1.59	11.33
Brent Reservoir	0.00	0.00	0.00	0.06	0.22	0.50	0.56	0.84	2.07	17.89
Wembley	0.00	0.00	0.00	0.00	0.00	0.59	0.59	0.79	2.56	5.09
Gladstone Park	0.00	0.00	0.00	0.00	0.00	0.17	0.17	1.02	1.69	5.91
Stonebridge Park	0.00	0.00	0.00	0.00	0.00	0.38	0.63	1.51	2.52	7.93
Ealing Castlebar	0.00	0.00	0.00	0.00	0.00	0.33	0.41	1.25	2.74	12.04
Brentside School	0.00	0.00	0.11	0.11	0.11	0.44	0.65	1.20	2.50	9.19
Northolt Aero.	0.00	0.04	0.04	0.24	0.33	0.57	0.81	1.51	2.64	24.58
Hayes	0.00	0.00	0.04	0.04	0.04	0.12	0.20	0.74	1.92	25.59
Mogden	0.00	0.00	0.00	0.00	0.00	0.13	0.25	1.01	1.90	7.90
Ruislip	0.00	0.00	0.11	0.11	0.16	0.37	0.58	1.21	2.99	19.08
Hampton	0.00	0.00	0.05	0.19	0.29	0.43	0.62	1.48	2.63	20.91
Hogsmill	0.00	0.00	0.00	0.06	0.12	0.29	0.52	1.27	2.30	17.38
Canbury Gdns.	0.00	0.00	0.09	0.09	0.18	0.27	0.36	1.16	1.70	11.20
Kew Obs.	0.00	0.03	0.10	0.13	0.20	0.47	0.57	1.10	2.00	30.03
Kew Stw	0.00	0.00	0.00	0.00	0.00	0.50	0.60	1.71	2.31	9.97
Sutton Stw	0.00	0.00	0.03	0.09	0.09	0.30	0.51	1.05	2.05	33.21
Raynes Pk Ps	0.00	0.00	0.00	0.00	0.17	0.78	0.86	1.47	2.59	11.59
Putney Heath	0.00	0.00	0.17	0.17	0.17	0.50	1.16	2.00	2.66	6.01
Banstead	0.00	0.00	0.00	0.14	0.29	0.71	1.28	2.28	3.85	7.02
Alderstead Heath	0.00	0.00	0.00	0.00	0.00	0.38	0.75	0.94	1.13	5.32
Crossness Stw	0.00	0.00	0.12	0.12	0.12	0.36	0.72	1.55	2.27	8.37
Orpington	0.00	0.00	0.00	0.00	0.00	0.55	0.55	1.29	2.39	5.44
Mean	0.00	0.002	0.04	0.08	0.13	0.40	0.61	1.35	2.31	
s.d	0.00	0.01	0.05	0.07	0.11	0.17	0.25	0.39	0.55	

Hampstead



Hayes

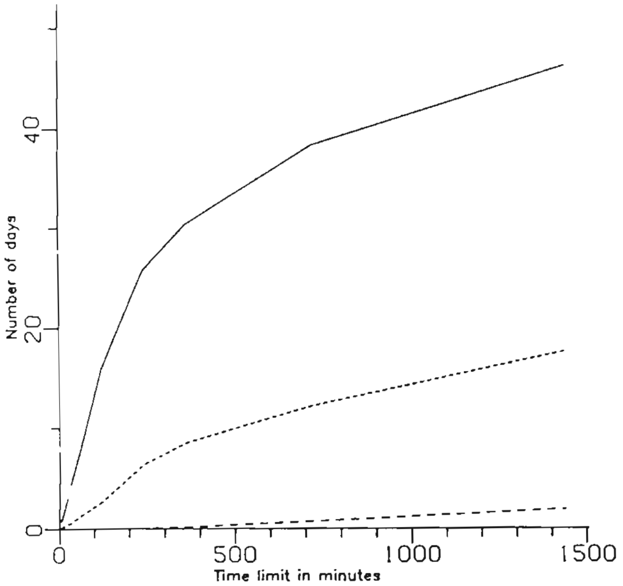


Figure 7.3.1a ***Number of days counted per year for which a given depth falls within a given duration (continuous line: depth = 5 mm; short dashes: depth = 10 mm; long dashes: depth = 25 mm).***

Average over 30 raingauges

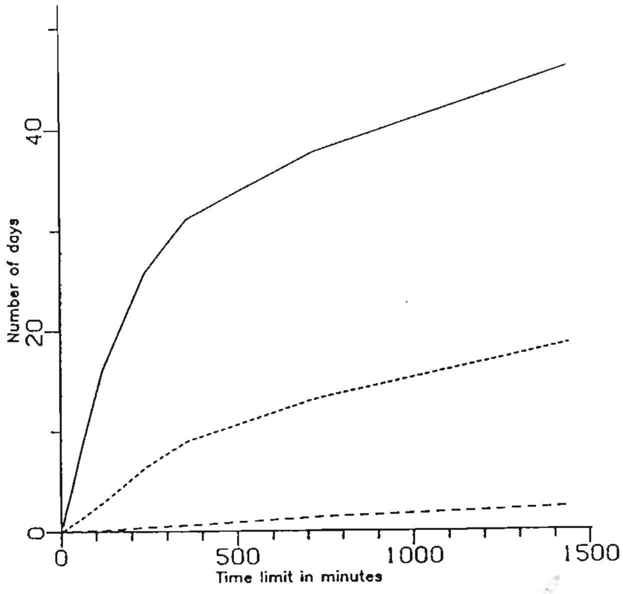
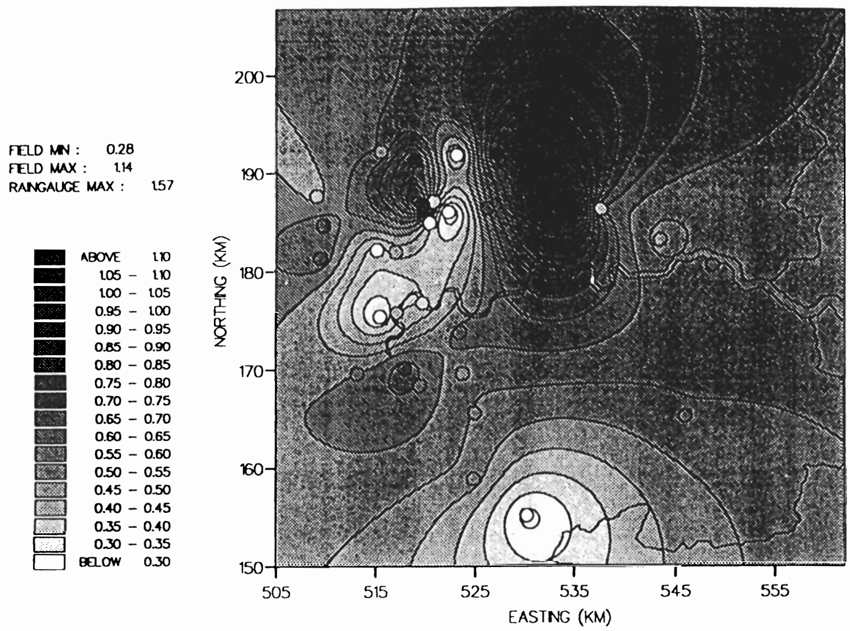


Figure 7.3.1b continued Number of days counted per year for which a given depth falls within a given duration (continuous line: depth = 5 mm; short dashes: depth = 10 mm; long dashes: depth = 25 mm).

At least 5 mm in less than 6 minutes



At least 5 mm in less than 15 minutes

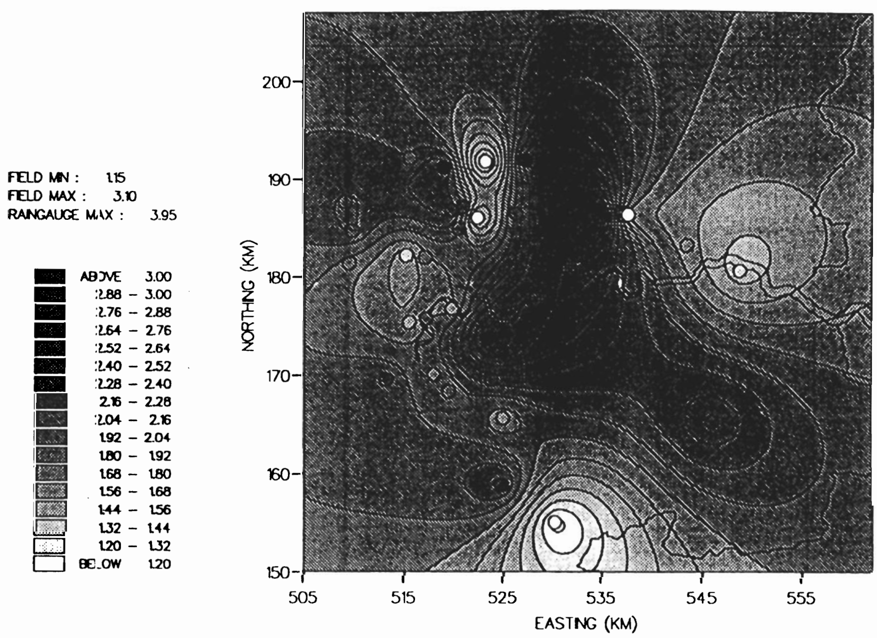
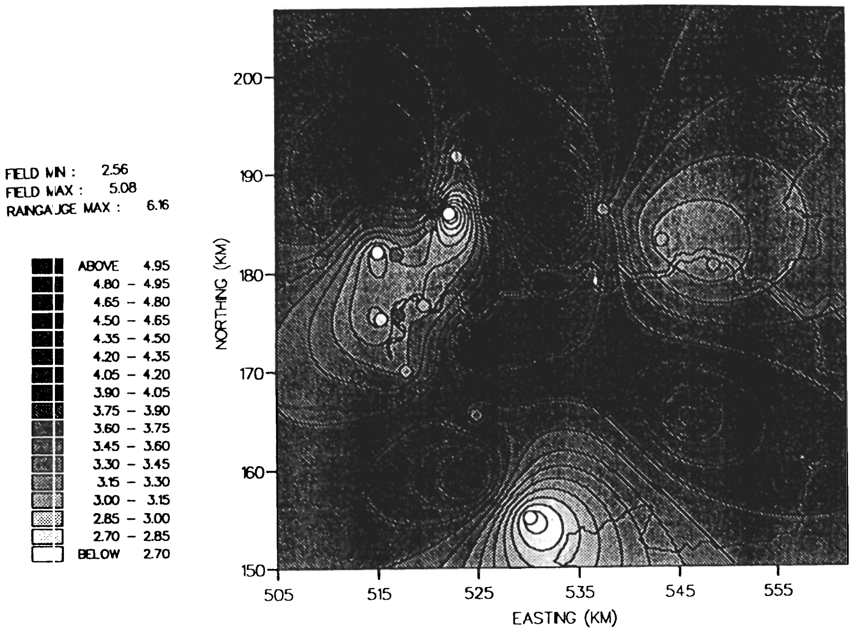


Figure 7.3.2a ***Map of number of days per year for which a given depth falls within a given duration***

At least 5 mm in less than 30 minutes



At least 5 mm in less than 60 minutes

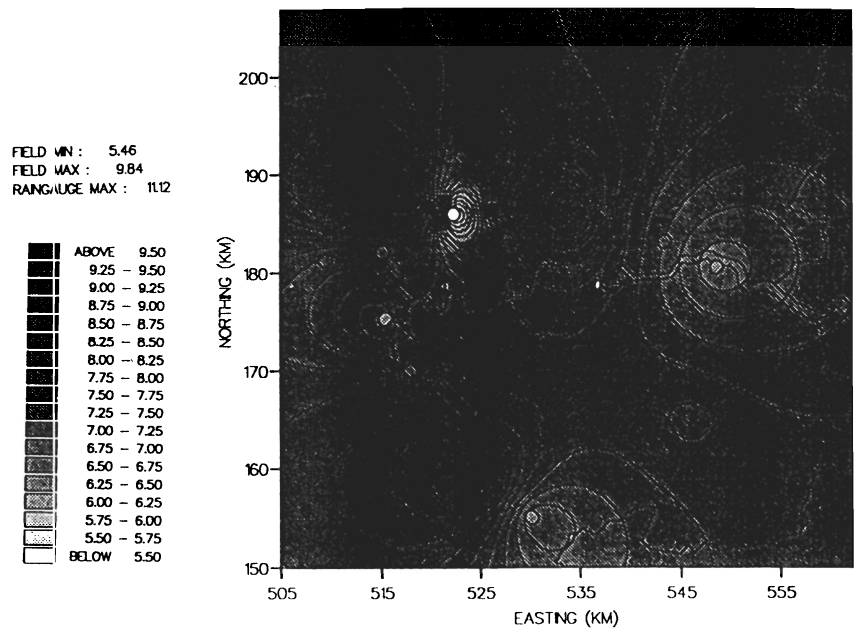
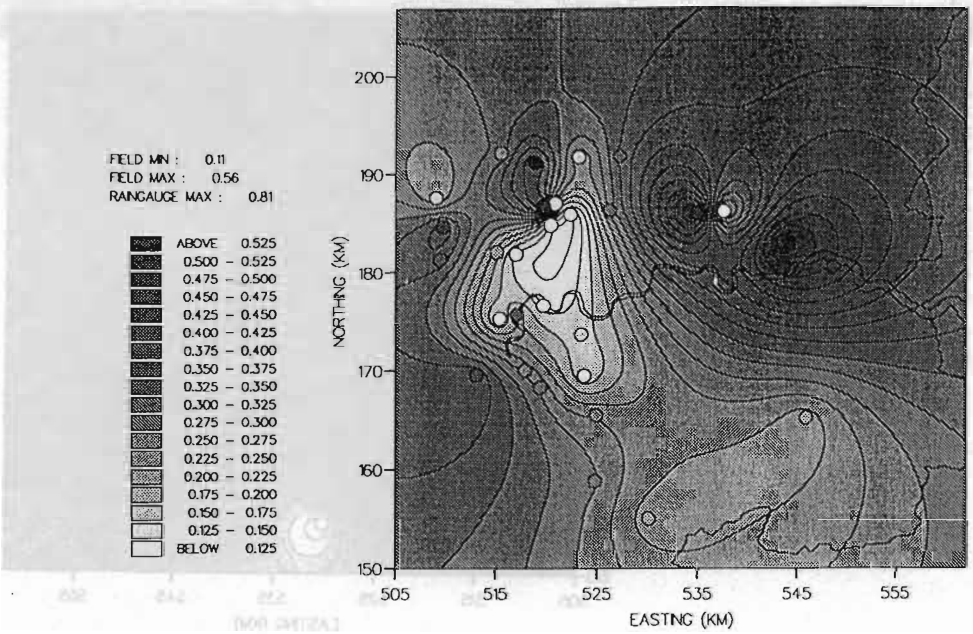


Figure 7.3.2b *Map of number of days per year for which a given depth falls within a given duration*

At least 10 mm in less than 15 minutes



At least 10 mm in less than 30 minutes

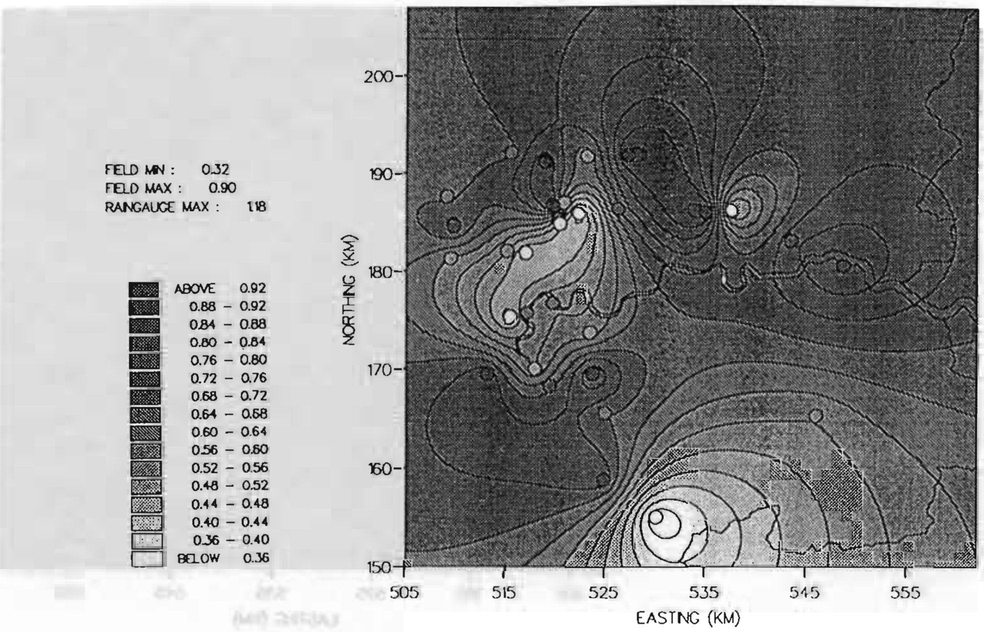
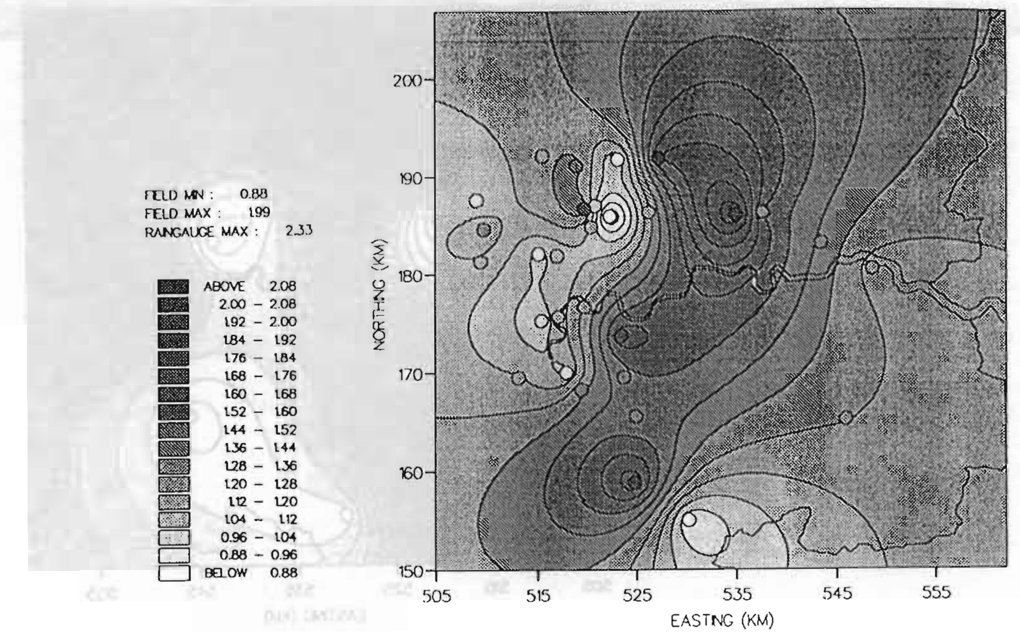


Figure 7.3.2c *Map of number of days per year for which a given depth falls within a given duration*

At least 10 mm in less than 60 minutes



At least 10 mm in less than 120 minutes

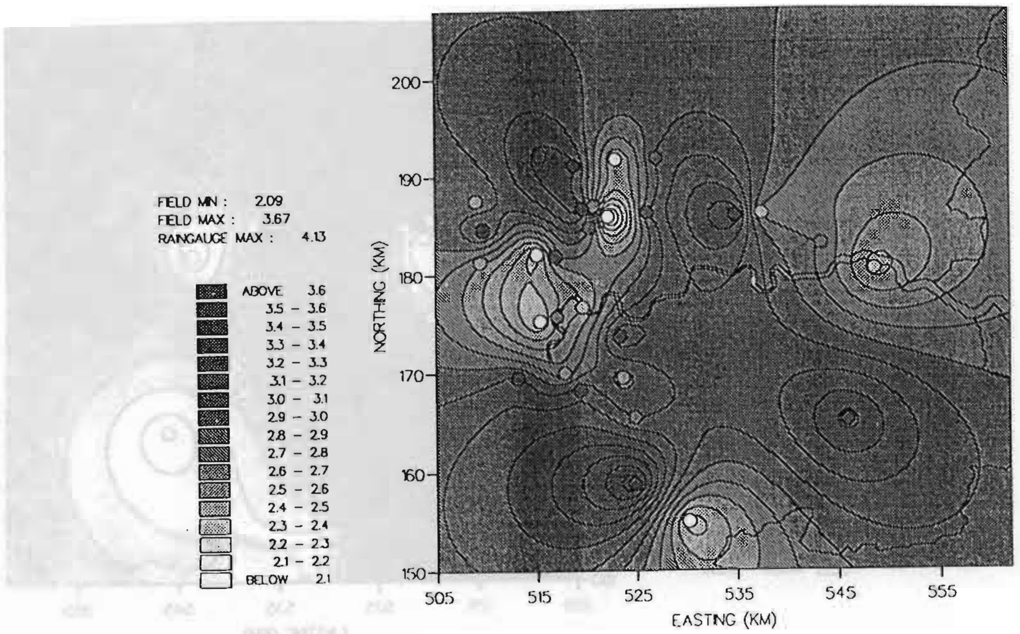
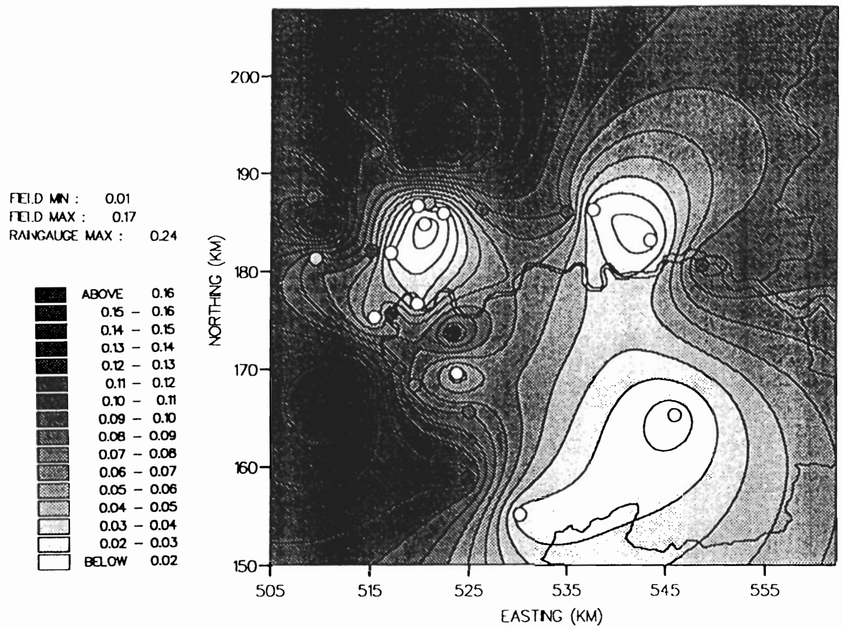


Figure 7.3.2d *Map of number of days per year for which a given depth falls within a given duration*

At least 25 mm in less than 60 minutes



At least 25 mm in less than 120 minutes

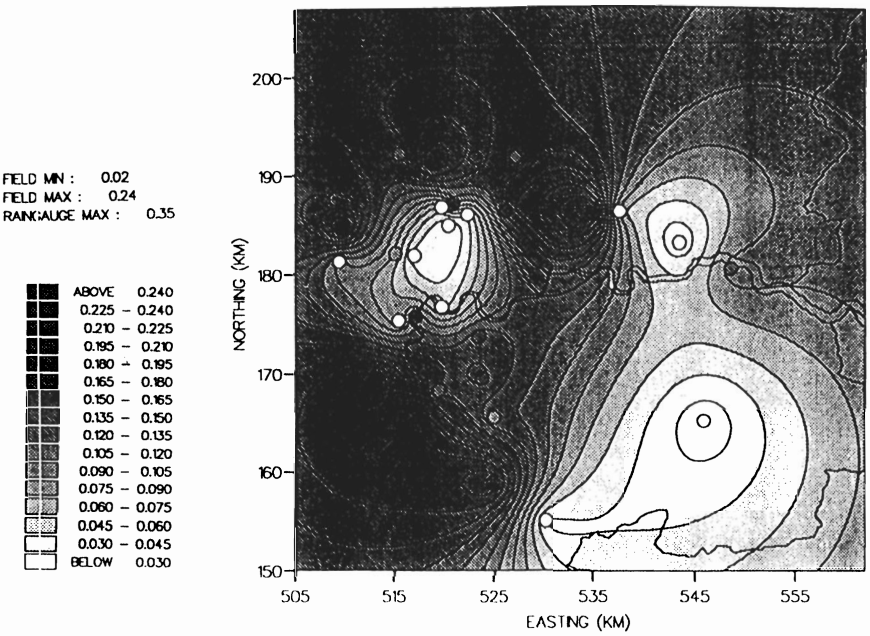
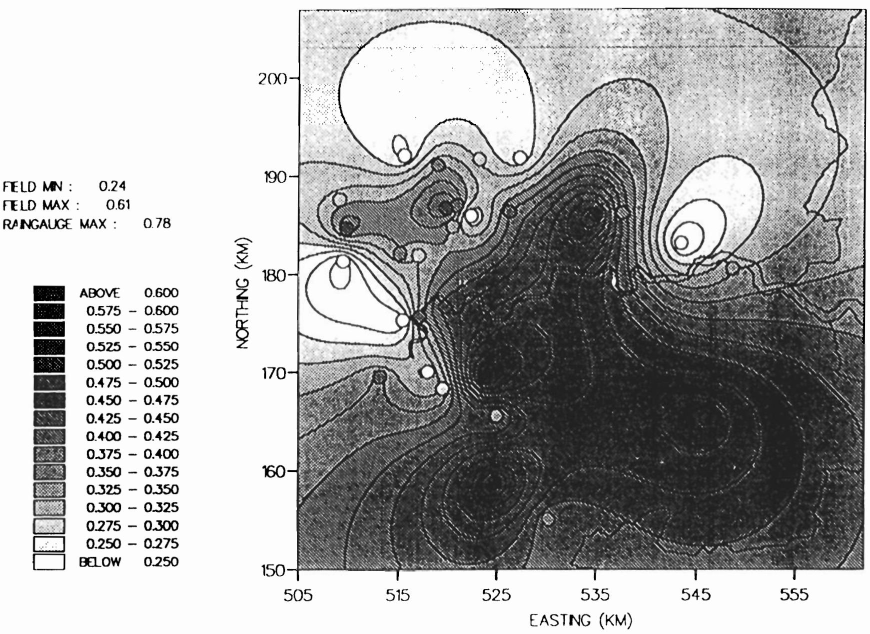


Figure 7.3.2e *Map of number of days per year for which a given depth falls within given a duration*

At least 25 mm in less than 4 hours



At least 25 mm in less than 24 hours

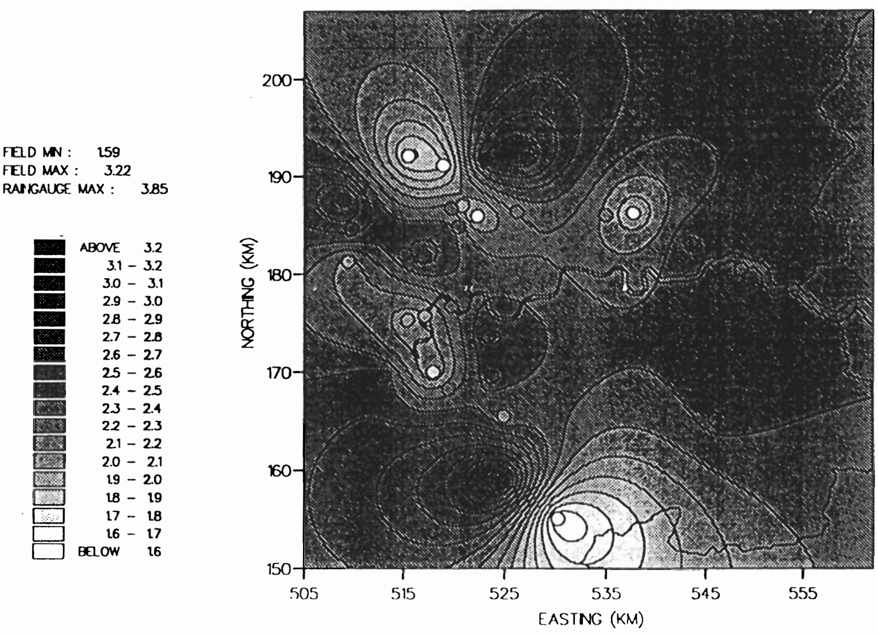
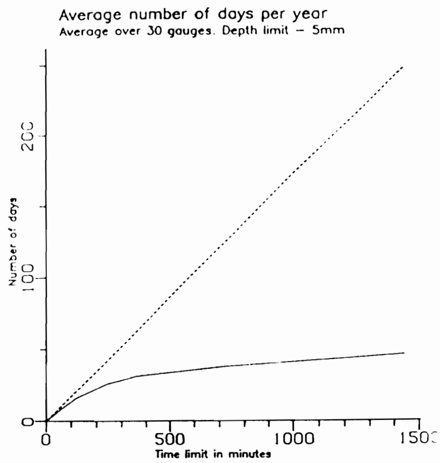
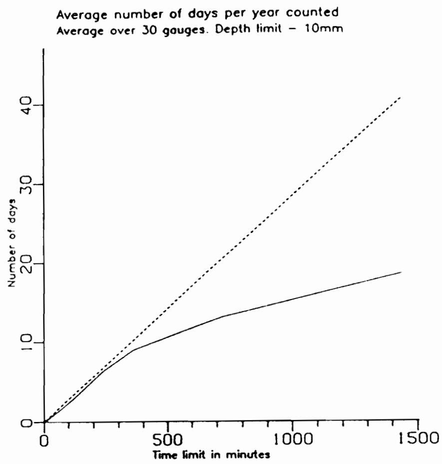


Figure 7.3.2f ***Map of number of days per year for which a given depth falls within a given duration***

Depth = 5 mm



Depth = 10 mm



Depth = 25 mm

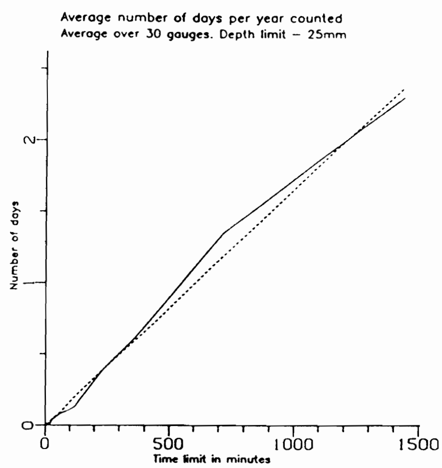
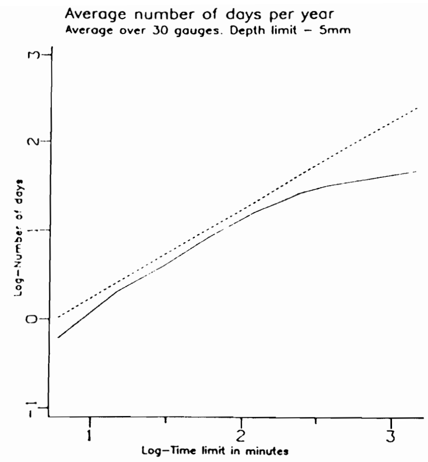
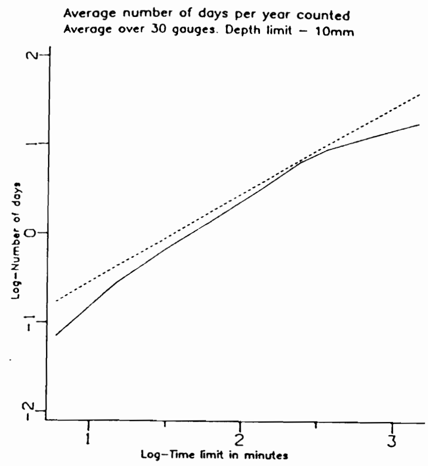


Figure 7.3.3 ***Plot of number of days per year for which a given depth falls within a given duration (continuous line: PEPR analysis; dashed line: revised Bilham formula, eqn. (7.3.1))***

Depth = 5 mm



Depth = 10 mm



Depth = 25 mm

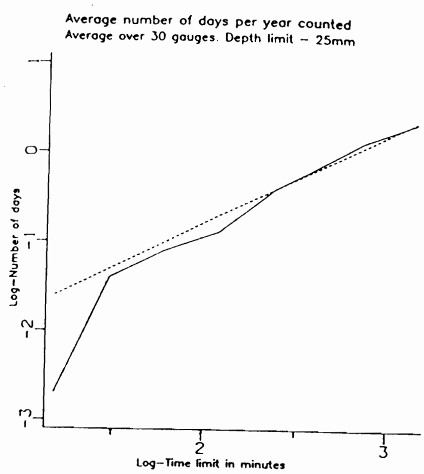


Figure 7.3.4 ***Plot of number of days per year for which a given depth falls within a given duration (log graph); (continuous line: PEPR analysis; dashed line: revised Bilham formula, eqn. (7.3.1))***

Table 7.3.3 Comparison of values of n obtained using the PEPR data set, the revised Bilham formula (7.3.1) and equation (7.3.2)

(a) $r = 5$ mm

	Time (minutes)								
	6	15	30	60	120	240	360	720	1440
PEPR	1.04	2.59	5.18	10.36	20.73	41.45	62.18	124.36	248.72
Bilham (eqn. 7.3.1)	0.61	2.04	3.91	8.32	16.01	25.74	31.09	37.73	46.00
(eqn. 7.3.2)	0.79	2.06	2.84	3.33	3.60	3.75	3.80	3.85	3.88

(b) $r = 10$ mm

	Time (minutes)								
	6	15	30	60	120	240	360	720	1440
PEPR	0.17	0.43	0.85	1.70	3.41	6.81	10.22	20.44	40.87
Bilham (eqn. 7.3.1)	0.07	0.28	0.64	1.32	2.87	6.36	8.99	13.08	19.36
(eqn. 7.3.2)	0.05	0.35	0.67	0.89	1.09	1.18	1.21	1.24	1.26

(c) $r = 25$ mm

	Time (minutes)								
	6	15	30	60	120	240	360	720	1440
PEPR	0.01	0.03	0.05	0.10	0.20	0.40	0.59	1.19	2.38
Bilham (eqn. 7.3.1)	0.00	0.00	0.04	0.08	0.13	0.40	0.61	1.35	2.31
(eqn. 7.3.2)	0.00	0.02	0.08	0.17	0.26	0.31	0.33	0.36	0.37

Table 7.3.4 Comparison of average number of occurrences of various storms per 10 years which Bilham obtained in 1935 for England and Wales and those obtained from the PEPR data set for London

(a) r = 5 mm

	Time (minutes)			
	6	15	30	60
Bilham	8.2	20.6	44.1	92.3
PEPR	6.1	20.4	39.1	53.2

(b) r = 10 mm

	Time (minutes)			
	15	30	60	120
Bilham	3.8	7.7	14.0	32.7
PEPR	2.8	6.4	13.2	28.7

(c) r = 25 mm

	Time (minutes)			
	1	2	5	24
Bilham	1.0	1.5	4.4	22.7
PEPR	0.8	1.3	4.0 (4 hours) 6.1 (6 hours)	23.1

7.4 A RE-EXAMINATION OF THE BILHAM FORMULA FOR STORMS OVER LONDON

7.4.1. Background

In the publication British Rainfall for 1935 Bilham presented an analysis of heavy rainfalls of short duration. This analysis was based on 12 raingauge records in England and Wales for the decade 1925-35. The raingauges included three from London, at Campden Square, Croydon and Kew Observatory. The records were reduced to counts of the number of days in the decade, n', on which specified amounts of rain in inches, r', fell in a specified duration in hours, t. This allowed the relation between n', r' and t to be examined and resulted in the well known Bilham formula

$$n' = 1.25t(r'+0.1)^{-3.55}. \qquad (7.4.1)$$

A re-examination of the analysis of Bilham was undertaken by D.K. Holland of the UK Meteorological Office in 1964, using records up to 1962, and published as Hydrological Memorandum No. 33, "Rainfall Intensity Frequency Relationships in Britain". This suggested a scaling up by a factor of 10/9 to give

$$n' = 1.39t(r'+0.1)^{-3.55} \qquad (7.4.2)$$

and a modified formula for intensities greater than 1.25 ins hr^{-1} (~ 32 mm hr^{-1})

$$n' = r'\exp(1-0.8r'/t)(r'+0.1)^{-3.55}. \qquad (7.4.3)$$

The latter formula was inspired by considering the relationship between return period, T = 10/n' years, and rainfall intensity, r'/t, considering the latter as an extreme variable (because of its computation as a daily peak value) of Gumbel form. A reprint of the Memorandum issued in 1968 contained an Appendix which served to clarify the form of the above equation and to tabulate the revised overall relationship.

7.4.2. Analysis of the PEPR records

The availability of the PEPR rainfall records over the London area provides the opportunity to examine the applicability of the Bilham formula, and its revisions, over the London area and to develop a more appropriate relationship if necessary. Records from 30 raingauges, all with at least 5 years of data and free from suspect data, were used. The maximum depth of a given duration within a day was computed for durations of 0.1, 0.25, 0.5, 1, 2, 4, 6, 12 and 24 hours and used to count the days on which a given maximum depth occurred, using depths of 2, 5, 10, 20, 25 and 50 mm. The counts per year, n (=n'/10), averaged for the 30 raingauges are tabulated for these depths and durations in Table 7.4.1. Figure 7.4.1 presents the table in graphical form, plotting for each of the six depths the counts against duration: as the depth increases the relation tends progressively towards a straight line. The counts for a given depth have been standardised by dividing by the maximum count for that depth.

An exponential relation for small depths

The exponential form of these curves for small depths suggests a relation of the form

$$n = a - b\ e^{ct}. \qquad (7.4.4)$$

where a, b and c are parameters. Fitting of this relation for depths of 5, 10 and 25 mm yielded the following equations

$r = 5$ mm $\qquad n = 44.5 - 44.4\ e^{-0.2t}$

$r = 10$ mm $\qquad n = 21.0 - 21.2\ e^{-0.09t}$

$r = 25$ mm $\qquad n = 5.93 - 5.99\ e^{-0.02t}$

The similarity of values for a and b, and their decrease along with c with increasing depth (in mm), r, suggests the modified form

$$n = ar^{b}\{1 - \exp(cr^{d}t^{e})\}. \qquad (7.4.5)$$

Fitting yielded the following parameter estimates: a = 176.3, b = -0.81, c = -2.64, d = -1.46 and e = 0.82. However, the relation proved to be biased giving a consistent overprediction. As a result the modified form

$$n = ar^{b}\{1 - \exp(cr^{d}t^{e})\} + fr + g \qquad (7.4.6)$$

was investigated, yielding the estimates a = 179.5, b = -0.83, c = -2.45, d = -1.45, e = 0.85, f = 0.02, g = -0.98. (The addition of a term ht on the right hand side provided little improvement). Whilst improvement was achieved at lower intensities, problems arise with negative predicted counts at higher intensities. Relations of the form $n = at^b/(r^c - d)$ and $n = at^b/r^c$ were also tried but proved worse than the exponential relation of equation (7.4.6).

A composite relation

A conclusion drawn from the above curve fitting experiments is that the exponential-type relation of equation (7.4.6) provides improved fit over the Gumbel and Bilham type formulae for lower rainfall intensities. This suggests that a composite set of

Table 7.4.1 ***Counts per year for different rainfall depths and durations obtained using the PEPR raingauge dataset for London***

Rainfall depth (mm)	Duration (hours)								
	0.10	0.25	0.50	1.0	2.0	4.0	6.0	12.0	24.0
2	5.90	13.92	24.87	40.36	55.43	65.46	69.29	75.07	82.70
5	0.61	2.04	3.91	8.32	16.05	25.74	31.09	37.73	46.02
10	0.07	0.28	0.64	1.32	2.87	6.36	8.99	13.08	18.59
20	0.00	0.02	0.08	0.15	0.33	0.81	1.32	2.55	4.12
25	0.00	0.01	0.04	0.08	0.13	0.40	0.61	1.35	2.31
50	0.00	0.00	0.00	0.00	0.02	0.03	0.04	0.10	0.25

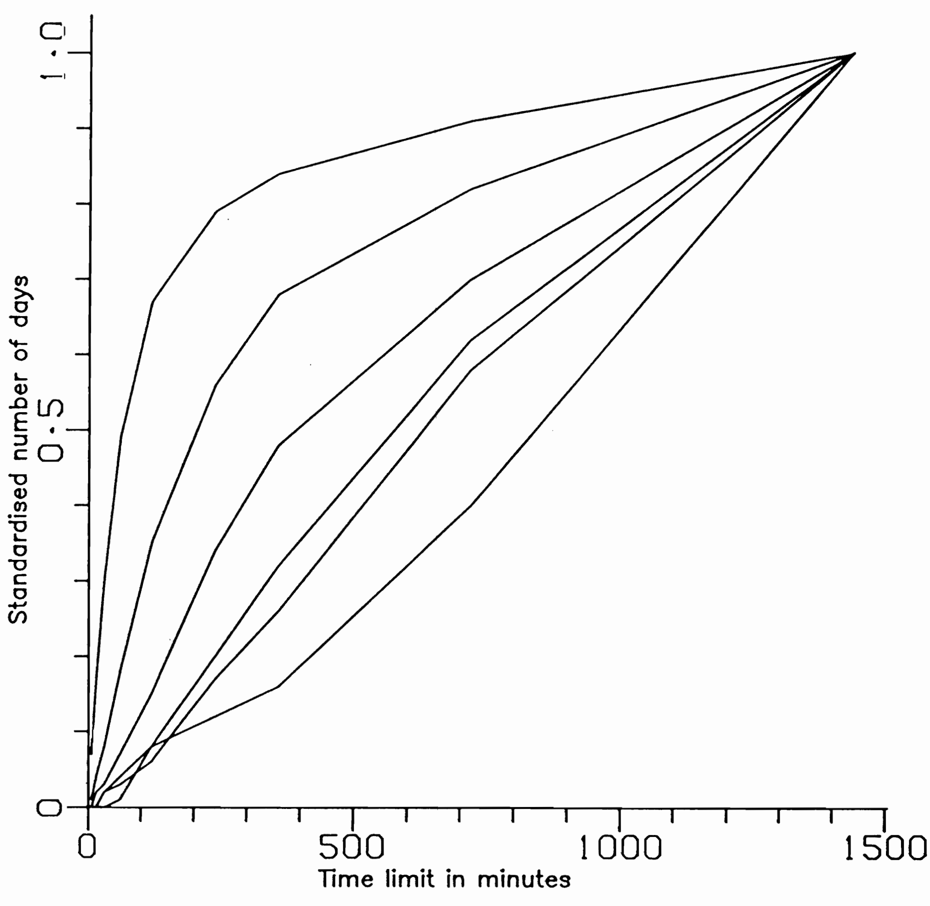


Figure 7.4.1 ***Counts per year (standardised) against duration for rainfall depths in mm of 2 (top curve), 5, 10, 20, 25 and 50 (bottom curve).***

formulae be developed from these three types of formulae. A generalised type of Bilham formula was used of the form

$$n = at^{b}(r+c)^{d}. \qquad (7.4.7)$$

This was used over the depth and duration ranges employed by Bilham and over other ranges for which the data suggested a Bilham-type relation. The ranges are tabulated below and the parameter values obtained are a = 1.48 x 10^4, b = 1.1, c = 2.54 and d = -3.65.

Depth mm	Range of durations hours	Implied range of rainfall intensities mm hr^{-1}
2	0.1 to 0.25	20 to 8
5	0.1 to 2	50 to 2.5
10	0.25 to 6	40 to 1.7
20	0.5 to 12	40 to 1.7
25	1 to 24	25 to 1
50	2 to 24	50 to 2.1

The rainfall intensity threshold of 32 mm hr^{-1}, above which a Gumbel-type relation was found to hold by the Meteorological Office study, was also supported by analysis of the PEPR records. The generalised form of Gumbel relation

$$n = ar\exp(1-br/t)(r+c)^{d} \qquad (7.4.8)$$

was fitted, giving parameter values of a = 136.5, b = 0.024, c = 2.54 and d = -3.36.

The exponential form of relation (equation (7.4.6)) was reconsidered in the light of the revised Bilham and Gumbel formulaes' superior performance at higher intensities. Fitting was constrained to use data points in the ranges tabulated below and the relation modified to the form

$$n = ar^{b}\,c^{r}\{1-\exp(dr^{e}\,t^{f})\}+g/r+h. \qquad (7.4.9)$$

Depth mm	Range of durations hours	Implied range of rainfall intensities mm hr^{-1}
2	0.5 to 24	4 to 0.08
5	1 to 24	5 to 0.21
10	1 to 24	10 to 0.42
20	12 to 24	0.6 to 0.83

The following estimates for the parameters were obtained: a = 288.3, b = -0.52, c = 0.957, d = -2.76, e = -0.94, f = 0.33, g = -211.8 and h = 5.68.

Rainfall depths and durations for which the Bilham, Gumbel and exponential forms (equations (7.4.7), (7.4.8) and (7.4.9)) have been adopted to form a composite relation are summarised in Table 7.4.2. The notation G/B signifies equally good performance of the Gumbel and Bilham relations and B(G) indicates a marginally better fit was obtained for the Gumbel form but a preference for the Bilham form in forming the composite relation; data points in each case were used in fitting both the Gumbel and Bilham relations. Predicted values of the counts per year, n, using the composite relation are presented in Table 7.4.3 and may be compared with the PEPR

Table 7.4.2 The relations adopted for different rainfall depths and durations: B - Bilham, G - Gumbel and E - exponential

Rainfall depth (mm)	Duration (hours)								
	0.10	0.25	0.50	1.0	2.0	4.0	6.0	12.0	24.0
2	B	B	E	E	E	E	E	E	E
5	G	B	B	E	E	E	E	E	E
10	G	G	B	B	E	E	E	E	E
20	G	G	G/B	G/B	B	B	B	B	E
25	G	G	G/B	B	B(G)	B	B	B	B
50	G	G	G	G/B	G/B	G/B	B(G)	B	B

Table 7.4.3 Counts per year for different rainfall depths and durations predicted using the composite Bilham, Gumbel and exponential formulae (equations (7), (8) and (9))

Rainfall depth (mm)	Duration (hours)								
	0.10	0.25	0.50	1.0	2.0	4.0	6.0	12.0	24.0
2	4.70	12.87	25.29	40.23	53.73	64.95	70.22	76.89	80.88
5	0.63	2.02	4.33	8.97	16.87	25.19	30.12	38.33	45.86
10	0.07	0.29	0.68	1.45	2.93	6.60	8.95	13.28	17.89
20	0.00	0.03	0.08	0.17	0.40	0.78	1.22	2.62	4.57
25	0.00	0.01	0.04	0.08	0.18	0.38	0.59	1.26	2.70
50	0.00	0.00	0.00	0.01	0.02	0.04	0.06	0.11	0.26

data derived values in Table 7.4.1. The goodness of fit of the composite relation is ilustrated in Figure 7.4.2 for depths of 2, 5, 10, 20, 25 and 50 mm.

7.4.3. A depth-duration-return period table for London

The new Bilham, Gumbel and exponential relations have been used to construct a table giving the rainfall depth for different durations and return periods (Table 7.4.4). This allows a direct comparison to be made with the similar table presented in the Appendix to Memorandum No. 33 and reproduced here as Table 7.4.5. Note that, since the exponential relation only applies for return periods smaller than one year, it is not used in the construction of the table. Discontinuities at the crossover between Bilham and Gumbel type relations at the threshold of 32 mm hr^{-1} are smoothed out using a transition function which uses a weighted combination of estimates from the two relations. This gives equal weight to the Gumbel and Bilham derived rainfall depth values for durations either side of the threshold and weights of ¾ and ¼ for values at durations two steps removed from the threshold, for a given return period.

The revised table based on the PEPR rainfall data for London (Table 7.4.4) shows remarkable agreement with that previously obtained for England and Wales and published in the Appendix to Hydrological Memorandum No. 33, here reproduced as Table 7.4.5.

7.5 CONCLUSION

An analysis of the sub-hourly rainfall information contained in the PEPR dataset has allowed a re-examination of the Bilham-type relations to be undertaken. This analysis broadly confirms the validity of these relations over London. A modified relation has been established, but this is not radically different from that published in the Appendix to Hydrological Memorandum No. 33 issued in 1968 by the Meteorological Office.

Since 1968, and specifically with the completion of the Flood Studies Report in 1975, a radically different approach to storm return period has gained general acceptance for engineering design. Whilst the Bilham-type formulae are derived from a consideration of maximum depths falling within a given duration, the Flood Study approach considers the occurrence of a given depth and a given duration. The quantities are clearly different and the latter is now viewed as the more relevant for design. Consequently the re-examination of the Bilham formula utilising the PEPR dataset primarily serves to demonstrate a result for London which is broadly consistent with the original and subsequent Bilham-type analyses. The Flood Study approach should be the preferred one for engineering design.

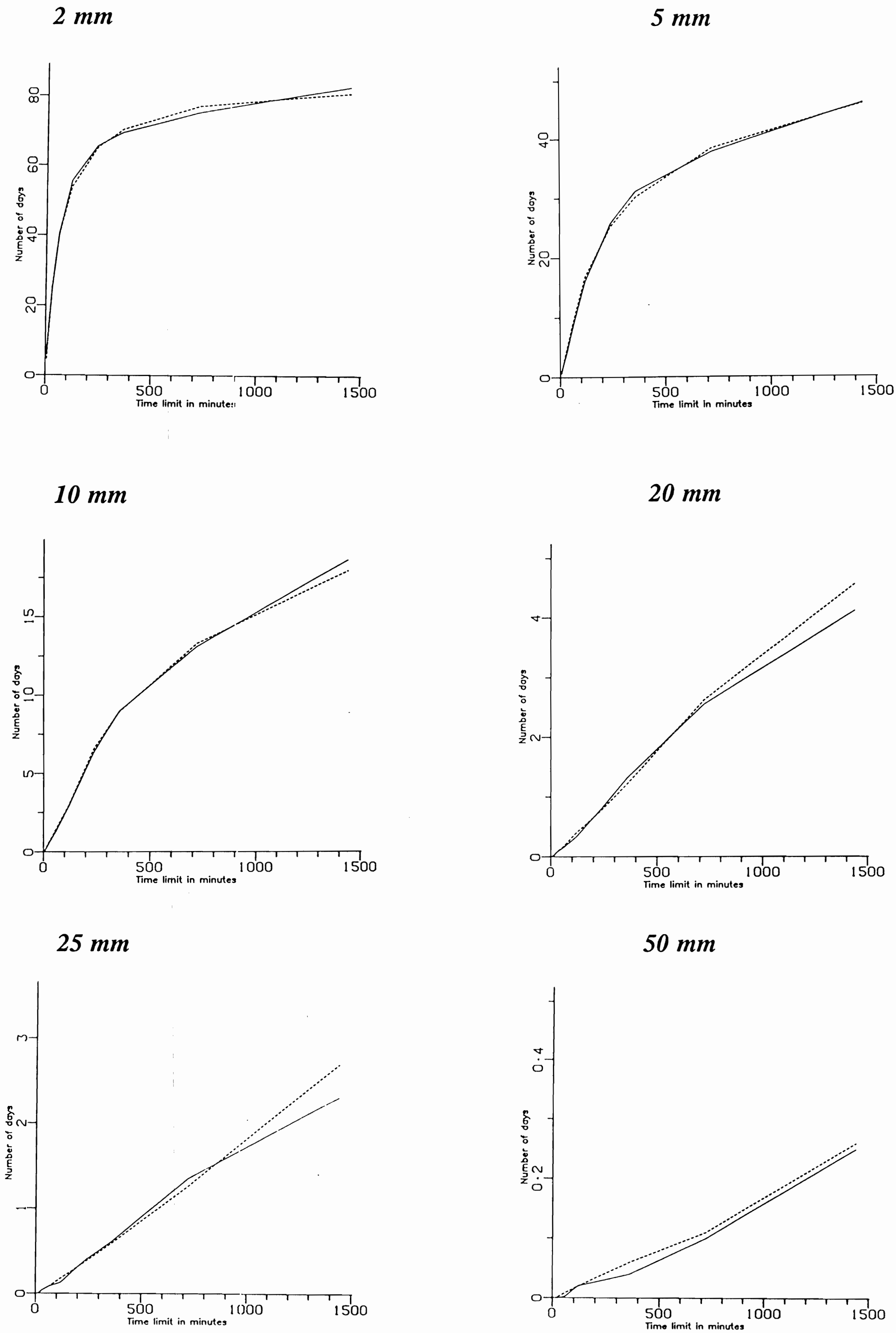


Figure 7.4.2 ***Counts per year against duration for various rainfall depths: PEPR derived values - continuous line, composite formulae estimate - dashed line.***

*Table 7.4.4 **Rainfall depths in mm for different storm durations and return periods obtained using the London PEPR dataset.***

Duration (minutes)	Return period (years) 1	2	5	10	20	50	100
2.0	2.1	2.8	3.7	4.4	5.1	6.1	6.8
2.5	2.5	3.3	4.4	5.2	6.1	7.2	8.1
3.0	2.8	3.7	4.9	5.9	6.9	8.2	9.3
3.5	3.0	4.1	5.4	6.5	7.6	9.2	10.4
4.0	3.3	4.4	5.9	7.1	8.4	10.1	11.4
4.5	3.5	4.7	6.4	7.7	9.0	10.9	12.4
5.0	3.7	5.0	6.8	8.2	9.6	11.7	13.3
5.5	3.9	5.2	7.1	8.6	10.2	12.4	14.2
6.0	4.1	5.5	7.5	9.1	10.8	13.1	15.0
7.0	4.4	5.9	8.1	9.9	11.8	14.5	16.6
8.0	4.6	6.3	8.7	10.7	12.7	15.7	18.1
9.0	4.9	6.6	9.2	11.3	13.6	16.8	19.4
10.0	5.3	6.9	9.7	11.9	14.4	17.9	20.7
11.0	5.5	7.2	10.1	12.5	15.1	18.9	21.9
12.0	5.9	7.4	10.5	13.0	15.8	19.8	23.0
13.0	6.2	7.6	10.8	13.5	16.4	20.7	24.1
14.0	6.4	7.8	11.1	14.0	17.0	21.5	25.2
15.0	6.6	8.2	11.4	14.4	17.6	22.3	26.1
16.0	6.8	8.5	11.7	14.8	18.1	23.0	27.1
17.0	7.0	8.8	12.0	15.2	18.6	23.7	28.0
18.0	7.1	9.1	12.2	15.5	19.1	24.4	28.8
19.0	7.3	9.3	12.5	15.8	19.6	25.1	29.6
20.0	7.4	9.5	12.8	16.2	20.0	25.7	30.4
25.0	8.1	10.4	13.8	17.5	21.9	28.5	34.0
30.0	8.7	11.1	14.7	18.6	23.4	30.8	37.0
35.0	9.3	11.7	15.6	19.5	24.7	32.7	39.6
40.0	9.8	12.3	16.6	20.4	25.8	34.4	41.9
45.0	10.2	12.9	17.3	21.3	26.6	35.9	43.9
50.0	10.6	13.4	17.9	22.2	27.4	37.2	45.7
55.0	11.0	13.8	18.5	22.9	28.2	38.4	47.4
60.0	11.3	14.3	19.0	23.6	29.0	39.4	48.9
70.0	12.0	15.1	20.1	24.8	30.5	41.0	51.5
80.0	12.6	15.8	21.0	25.9	31.9	42.3	53.7
90.0	13.2	16.4	21.9	27.0	33.1	43.7	55.6
100.0	13.7	17.0	22.6	27.9	34.3	44.9	56.6
110.0	14.1	17.6	23.4	28.8	35.3	46.2	57.5
120.0	14.6	18.2	24.1	29.6	36.4	47.5	59.0
180.0	16.8	20.8	27.5	33.8	41.4	54.0	65.7
240.0	18.6	23.0	30.2	37.1	45.4	59.1	72.0
300.0	20.0	24.7	32.5	39.9	48.7	63.4	77.1
360.0	21.3	26.3	34.5	42.3	51.6	67.1	81.6
420.0	22.4	27.6	36.3	44.4	54.2	70.4	85.6
480.0	23.5	28.9	37.9	46.3	56.5	73.4	89.3
540.0	24.4	30.0	39.3	48.1	58.7	76.1	92.6
600.0	25.3	31.1	40.7	49.7	60.6	78.7	95.6
660.0	26.1	32.1	41.9	51.2	62.5	81.0	98.5
720.0	26.8	33.0	43.1	52.7	64.2	83.2	101.2
1080.0	30.6	37.6	49.0	59.8	72.9	94.4	114.7
1440.0	33.7	41.2	53.7	65.5	79.7	103.2	125.3

Table 7.4.5 ***Rainfall depths in mm for different storm durations and return periods: from Appendix to Hydrological Memorandum No. 33***

Duration (minutes)	Return period (years) 1	2	5	10	20	50	100
2.0	2.3	2.9	3.6	4.2	4.7	5.5	6.1
2.5	2.7	3.4	4.2	4.9	5.6	6.5	7.2
3.0	3.1	3.8	4.8	5.6	6.4	7.5	8.3
3.5	3.4	4.2	5.4	6.2	7.1	8.3	9.3
4.0	3.7	4.6	5.9	6.8	7.8	9.2	10.2
4.5	4.0	5.0	6.3	7.4	8.5	10.0	11.1
5.0	4.2	5.3	6.8	7.9	9.1	10.7	12.0
5.5	4.5	5.6	7.2	8.4	9.7	11.4	12.8
6.0	4.7	5.9	7.5	8.9	10.2	12.1	13.6
7.0	5.1	6.4	8.2	9.7	11.3	13.4	15.1
8.0	5.4	6.8	8.9	10.5	12.2	14.6	16.5
9.0	5.7	7.2	9.4	11.2	13.1	15.7	17.8
10.0	6.0	7.6	10.0	11.9	13.9	16.8	19.0
11.0	6.2	8.0	10.5	12.5	14.7	17.7	20.2
12.0	6.4	8.3	10.9	13.1	15.4	18.7	21.3
13.0	6.7	8.6	11.3	13.6	16.1	19.6	22.3
14.0	6.8	8.8	11.7	14.1	16.7	20.4	23.3
15.0	7.0	9.1	12.1	14.6	17.3	21.2	24.3
16.0	7.2	9.3	12.4	15.1	17.9	22.0	25.2
17.0	7.4	9.5	12.8	15.5	18.4	22.7	26.1
18.0	7.5	9.7	13.1	15.9	19.0	23.4	27.0
19.0	7.7	9.9	13.4	16.3	19.5	24.1	27.8
20.0	7.8	10.1	13.6	16.6	19.9	24.7	28.6
25.0	8.5	10.9	14.8	18.3	22.0	27.6	32.2
30.0	9.1	11.6	15.8	19.6	23.8	30.0	35.2
35.0	9.6	12.2	16.6	20.7	25.3	32.2	37.9
40.0	10.1	12.8	17.3	21.6	26.6	34.0	40.3
45.0	10.5	13.3	18.0	22.4	27.7	35.7	42.5
50.0	10.9	13.8	18.6	23.2	28.7	37.2	44.4
55.0	11.3	14.2	19.2	23.9	29.5	38.5	46.2
60.0	11.6	14.6	19.7	24.5	30.3	39.7	47.8
70.0	12.2	15.4	20.7	25.7	31.8	41.8	50.7
80.0	12.8	16.1	21.6	26.8	33.1	43.6	53.1
90.0	13.3	16.7	22.4	27.8	34.3	45.2	55.3
100.0	13.8	17.3	23.2	28.7	35.4	46.6	57.2
110.0	14.2	17.8	23.9	29.5	36.5	47.9	58.8
120.0	14.6	18.4	24.5	30.3	37.4	49.2	60.4
180.0	16.7	20.9	27.8	34.3	42.3	55.5	68.0
240.0	18.4	22.9	30.3	37.4	46.0	60.4	73.9
300.0	19.7	24.5	32.5	40.0	49.2	64.4	78.9
360.0	20.9	25.9	34.3	42.3	51.9	68.0	83.2
420.0	21.9	27.2	36.0	44.3	54.3	71.1	87.0
480.0	22.9	28.3	37.4	46.0	56.5	73.9	90.4
540.0	23.7	29.4	38.8	47.7	58.5	76.5	93.5
600.0	24.5	30.3	40.0	49.2	60.4	78.9	96.4
660.0	25.2	31.2	41.2	50.6	62.1	81.1	99.1
720.0	25.9	32.1	42.3	51.9	63.7	83.2	101.7
1080.0	29.4	36.3	47.7	58.5	71.7	93.5	114.3
1440.0	32.1	39.5	51.9	63.7	77.9	101.7	124.1

8. Conditional Rainfall Forecasting

8.1 BACKGROUND

An application of the PEPR dataset which is of immediate relevance to operational flood warning is its use for rainfall forecasting. Historical rainfall records can be used to establish conditional relationships between rainfall amounts over consecutive time periods and the relationship used subsequently as a basis for conditional rainfall forecasting. In turn, these can be used as input to rainfall-runoff models in real-time to obtain flood forecasts for extended lead times.

One approach to the problem is to formally construct a stochastic rainfall model, for example based on distributions of storm features such as interarrival-time, storm duration and magnitude. Conditional probabilities are then worked out based on the nature of the storm features given past rainfall, for example the storm duration and magnitudes given that it has already been raining for t hours to a depth of r mm. A much simpler approach is to explore the dependence in the rainfall series, without formally identifying features within it, and exploit this dependence in forming a rainfall forecast. This may be achieved by modelling the rainfall series as a Markov chain in which the probabilities of transition from one "rain state" to another are used as the basis of forecasting. This approach is developed in the remainder of this section.

8.2 THE MARKOV CHAIN MODEL

The "rainfall states" to be considered are the rainfall rates assigned to non-overlapping categories. It has been found appropriate to adopt the categorisation into 12 intervals shown in Table 8.2.1. This allows the time series of rainfall for a given site to be transformed to the chain of n states $\{X_t\}$ for time periods $t = 0,\ldots,T$, where X_t is an n vector containing n-1 zeroes, and one unit entry corresponding to the rainfall category at time t; for example [000...010...0]. Now let a transition probability matrix, P, be defined such that the (j,k)th element p_{jk} is the probability of moving from state j to state k. An empirical estimate of this probability matrix is

$$P_{jk} = \frac{f_{jk}}{\sum\limits_{i=1}^{n} f_{ji}} \qquad j,k = 1,2,\ldots,n. \tag{8.2.1}$$

Table 8.2.1 Rainfall categorisation

Category	Rainfall rate (upper limit) mm hr^{-1}	Rainfall value assigned mm hr^{-1}
1	0	0
2	0.1	0.05
3	0.5	0.3
4	1	0.75
5	2	1.5
6	4	3
7	6	5
8	8	7
9	10	9
10	12	11
11	16	14
12	40	28

where f_{jk} is the number of transitions from state j to state k, over consecutive time intervals, counted using the rainfall record. The matrix F, of which f_{jk} is its (j,k)th element, is called the frequency count matrix and its j'th row total, denoted $F_{j+} = \sum_{i=1}^{n} f_{ji}$, is the total number of occurrences of state j in the rainfall record.

The choice of rainfall categories in Table 8.2.1 was arrived at so as to assure that F_{j+} is never too small. This was achieved by increasing the rainfall class range with higher, more infrequent, rainfall intensity. The choice was also guided by the categorisation used by the UK Meteorological Office in storing weather radar data.

Let X(0) denote the state vector at the forecast origin and $X(\tau)$ the state vector at lead time τ. Suppose also that the rainfall at the forecast origin is in state k. Then the theory of Markov chains gives as the probability of state $X(\tau)$

$$\mathrm{Prob}\big(X(\tau)\big) = P^{\tau}_{k.} = \left[p^{\tau}_{k1}\ p^{\tau}_{k2} \ldots p^{\tau}_{kn}\right] \tag{8.2.2}$$

where $P^{\tau}_{k.}$ denotes the vector formed by the k'th row of P^{τ}. In other words, the transition probability matrix P is multiplied by itself τ times and row k of the resulting matrix contains the probabilities of transition to each of the possible n states of rainfall intensity. The result of (8.2.2) follows from the definition of a Markov chain as a sequence of random variables where the t+1'th value, X_{t+1}, given all previous values $X_0, X_1, \ldots, X_t$ depends only on the last value, X_t, and not the previous t values $X_0, X_1, \ldots, X_{t-1}$.

The n probabilities can be used to define an empirical distribution function, $F_s(\tau)$, (i.e. probability of non-exceedence function) such that

$$\mathrm{Prob}\big(X(\tau) \le x_s\big) = F_s(\tau) = \sum_{i=1}^{s} p_{ki}^{\tau} \qquad s = 1,2,\ldots,n \tag{8.2.3}$$

where x_s may be chosen to be the mid-point value of the s'th rainfall class interval (see Table 8.2.1). Interpolation between the n values defining the empirical distribution function (and the two end points, 0 and 1) allows the rainfall with a given probability of non-exceedence to be obtained. The median value of rainfall, corresponding to a probability of 0.5, provides an estimate (forecast) of the rainfall at lead time τ. This will be denoted as $\hat{R}(\tau)$ which is the rainfall satisfying $\mathrm{Prob}(X(\tau) \le \hat{R}(\tau)) = 0.5$. An alternative estimator is provided by the mean (expected value)

$$\bar{R}(\tau) = \sum_{i=1}^{n} x_i \, p_{ki}^{\tau} \tag{8.2.4}$$

where x_i denotes the mid-value of the i'th rainfall class. The results that follow use the median estimator but trials indicate that use of the mean estimator is preferred.

A matrix of forecast rainfall values may be calculated for each possible state at the forecast origin and for each lead time. The resulting τ_{max} by n matrix is termed the "forecast matrix" and needs to be computed only once. Forecasting then proceeds as a simple "look-up table" procedure, choosing the appropriate entry in the forecast matrix for a required lead time and given initial state.

8.3 APPLICATION

The quality controlled PEPR hourly rainfall record for Hampton for the period 1954 to 1974 has been used to investigate the performance of the Markov conditional rainfall forecasting method. As a basis for assessment similar criterion to those developed to assess the local radar rainfall forecasting procedure have been used. Specifically, the root mean square log-error criterion

$$\text{rms log-error} = \sum_t e^2$$

where the log-error

$$e = \log\{(1+R)/(1+\hat{R})\}$$

has been employed. Here, R is the observed rainfall intensity and $\hat{R}$ is the forecast value. This error criterion has been calculated for each forecast lead time τ = 1, 2, 3, 4, 5 and 6 hours and the result plotted as a graph of root mean square log-error against lead time. The result obtained using a single transition probability matrix computed from the entire record (183125 time-steps) is shown in Figure 8.3.1 and the corresponding matrix displayed in Table 8.3.1(a). The error criterion obtained using a persistence forecast is also plotted in Figure 8.3.1 as a baseline for assessment.

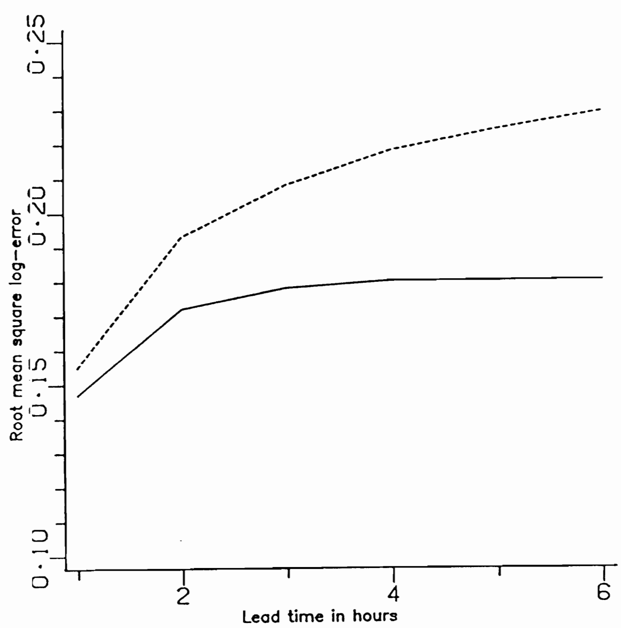


Figure 8.3.1 ***Root mean square log-error as a function of forecast lead time for the non-seasonal Markov chain forecast method and persistence (dashed line).***

It is reasonable to conjecture that the transition probability matrix exhibits a variation with time of year. To investigate this conjecture transition probability matrices have been calculated for the 12 months of the year and for the two seasons winter (90407) time-steps) and summer (92472 time-steps). Table 8.3.1(b) and (c) show the winter and summer matrices and Figure 8.3.2 shows the resulting log root mean square error against lead time plot obtained from the seasonal Markov chain forecast method.

Figure 8.3.3 shows the month-to-month variation in log root mean square error obtained from the monthly Markov chain forecast method. The largest errors are seen to occur in summer when the Markovian assumption might be expected to be least applicable.

Table 8.3.1 Transition probability matrix for Hampton hourly rainfall

(a) Non seasonal

	Rainfall rate (upper limit) mm hr^{-1}											
	0	0.1	0.5	1	2	4	6	8	10	12	16	40
0	0.931	0.052	0.011	0.003	0.002	0.001	0.000	0.000	0.000	0.000	0.000	0.000
0.1	0.417	0.455	0.088	0.022	0.013	0.004	0.001	0.000	0.000	0.000	0.000	0.000
0.5	0.173	0.318	0.302	0.116	0.063	0.022	0.005	0.001	0.001	0.000	0.000	0.000
1	0.086	0.205	0.288	0.217	0.149	0.042	0.012	0.001	0.000	0.000	0.000	0.000
2	0.071	0.152	0.215	0.194	0.238	0.107	0.017	0.003	0.002	0.001	0.000	0.000
4	0.039	0.124	0.164	0.171	0.247	0.191	0.046	0.010	0.004	0.002	0.001	0.001
6	0.036	0.107	0.156	0.124	0.178	0.244	0.107	0.027	0.009	0.004	0.004	0.004
8	0.033	0.067	0.167	0.100	0.167	0.167	0.150	0.067	0.000	0.050	0.017	0.017
10	0.136	0.000	0.182	0.136	0.091	0.136	0.091	0.182	0.045	0.000	0.000	0.000
12	0.000	0.091	0.182	0.182	0.091	0.273	0.091	0.091	0.000	0.000	0.000	0.000
16	0.250	0.125	0.000	0.000	0.125	0.125	0.000	0.125	0.000	0.000	0.000	0.250
40	0.000	0.000	0.222	0.000	0.000	0.222	0.000	0.111	0.111	0.000	0.000	0.333

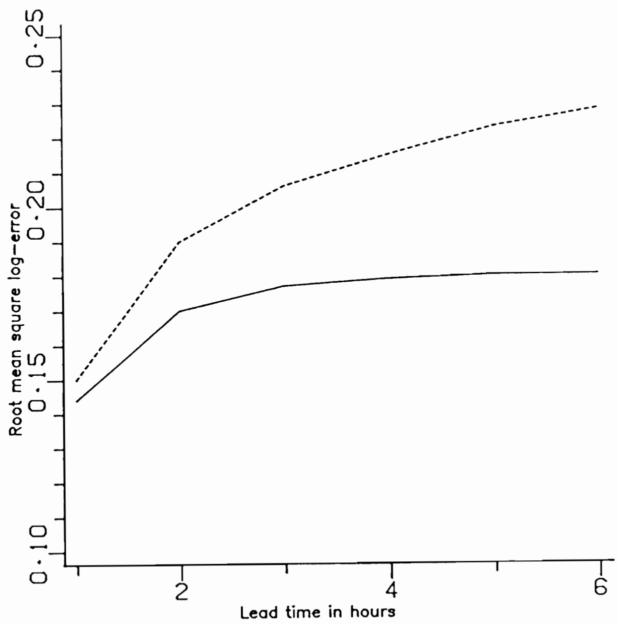
(b) Winter

	Rainfall rate (upper limit) mm hr^{-1}											
	0	0.1	0.5	1	2	4	6	8	10	12	16	40
0	0.926	0.056	0.012	0.003	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.1	0.409	0.464	0.092	0.020	0.011	0.003	0.001	0.000	0.000	0.000	0.000	0.000
0.5	0.153	0.324	0.314	0.119	0.064	0.022	0.003	0.000	0.000	0.000	0.000	0.000
1	0.069	0.193	0.297	0.237	0.145	0.044	0.012	0.002	0.001	0.000	0.000	0.000
2	0.056	0.140	0.230	0.194	0.255	0.107	0.017	0.002	0.001	0.000	0.000	0.000
4	0.038	0.113	0.145	0.170	0.277	0.193	0.050	0.008	0.004	0.000	0.000	0.000
6	0.028	0.075	0.160	0.142	0.208	0.236	0.104	0.038	0.009	0.000	0.000	0.000
8	0.000	0.043	0.174	0.174	0.174	0.043	0.130	0.130	0.000	0.130	0.000	0.000
10	0.125	0.000	0.250	0.375	0.000	0.125	0.125	0.000	0.000	0.000	0.000	0.000
12	0.000	0.000	0.333	0.333	0.333	0.000	0.000	0.000	0.000	0.000	0.000	0.000
16	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
40	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

(c) Summer

	Rainfall rate (upper limit) mm hr^{-1}											
	0	0.1	0.5	1	2	4	6	8	10	12	16	40
0	0.935	0.049	0.011	0.003	0.002	0.001	0.000	0.000	0.000	0.000	0.000	0.000
0.1	0.425	0.445	0.084	0.024	0.015	0.005	0.001	0.001	0.000	0.000	0.000	0.000
0.5	0.197	0.311	0.287	0.112	0.062	0.021	0.007	0.002	0.001	0.000	0.000	0.000
1	0.106	0.219	0.277	0.192	0.155	0.040	0.011	0.001	0.000	0.000	0.000	0.000
2	0.089	0.165	0.199	0.193	0.218	0.107	0.017	0.005	0.004	0.002	0.001	0.000
4	0.039	0.134	0.184	0.171	0.216	0.190	0.041	0.012	0.004	0.004	0.002	0.002
6	0.042	0.134	0.151	0.109	0.151	0.252	0.109	0.017	0.008	0.008	0.008	0.008
8	0.054	0.081	0.162	0.054	0.162	0.243	0.162	0.027	0.000	0.000	0.027	0.027
10	0.143	0.000	0.143	0.000	0.143	0.143	0.071	0.286	0.071	0.000	0.000	0.000
12	0.000	0.125	0.125	0.125	0.000	0.375	0.125	0.125	0.000	0.000	0.000	0.000
16	0.143	0.143	0.000	0.000	0.143	0.143	0.000	0.143	0.000	0.000	0.000	0.286
40	0.000	0.000	0.222	0.000	0.000	0.222	0.000	0.111	0.111	0.000	0.000	0.333

(a) Winter



(b) Summer

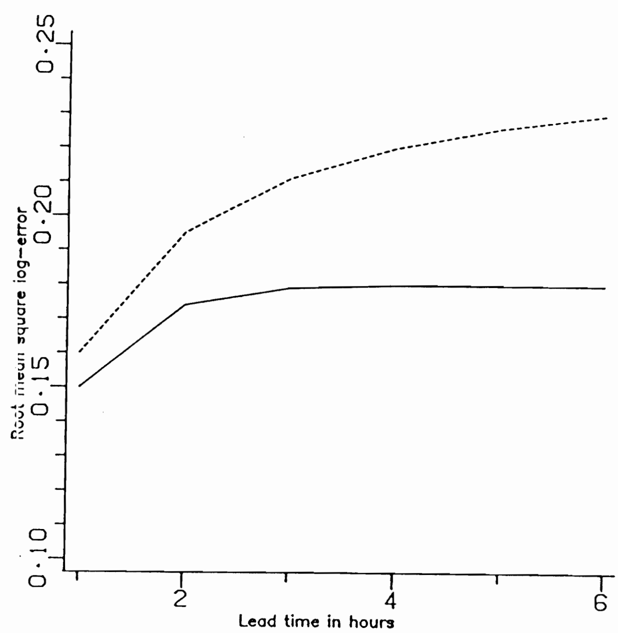


Figure 8.3.2 ***Root mean square log-error as a function of forecast lead time for the seasonal Markov chain forecast method and persistence (dashed line).***

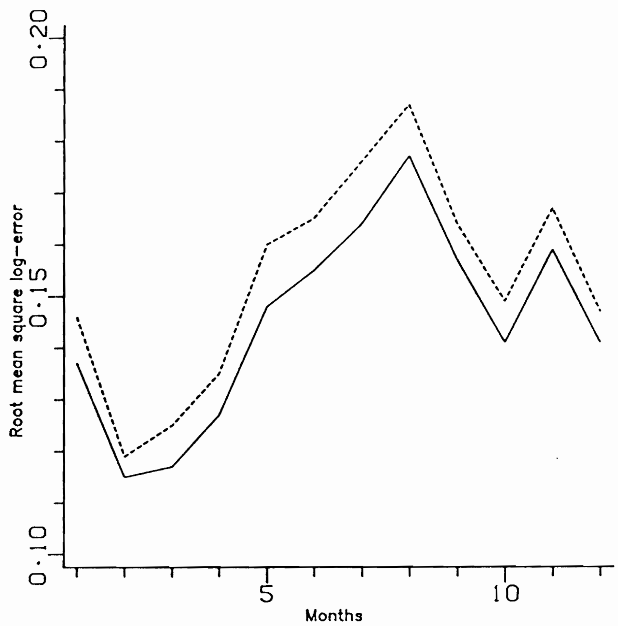


Figure 8.3.3 ***Root mean square log-error as a function of month of year for the monthly Markov chain forecast method and persistence (dashed line): the forecast lead time is 1 hour.***

A further property of the Markov chain models is the matrix of forecast rainfalls, corresponding to a 50% non-exceedence probability value, for given values of forecast origin state and lead time. This "forecast matrix", of dimension τ_{max} by n (6 by 12 in this case), is shown in Table 8.3.4 for the non-seasonal and winter and summer Markov chain models.

Table 8.3.4 Forecast matrix for Hampton giving the forecast category rainfall for a given forecast origin category rainfall and lead time

(a) Non-seasonal

Lead time	Forecast origin rainfall category (upper limit) mm hr^{-1}										
hr	0	0.1	0.5	1	2	4	6	8	10	12	16	40
1	0.000	0.009	0.057	0.232	0.443	0.758	1.078	1.350	1.125	1.125	1.500	6.000
2	0.000	0.000	0.024	0.048	0.125	0.207	0.253	0.299	0.256	0.280	0.204	0.920
3	0.000	0.000	0.000	0.021	0.031	0.042	0.048	0.077	0.047	0.066	0.040	0.231
4	0.000	0.000	0.000	0.000	0.007	0.016	0.020	0.025	0.018	0.024	0.012	0.047
5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.020
6	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

(b) Winter

Lead time	Forecast origin rainfall category (upper limit) mm hr^{-1}											
hr	0	0.1	0.5	1	2	4	6	8	10	12	16	40
1	0.000	0.010	0.068	0.250	0.473	0.841	1.091	1.291	0.450	0.525	0.000	0.000
2	0.000	0.000	0.028	0.076	0.157	0.242	0.295	0.372	0.189	0.218	0.000	0.000
3	0.000	0.000	0.006	0.028	0.038	0.049	0.091	0.137	0.042	0.049	0.000	0.000
4	0.000	0.000	0.000	0.006	0.015	0.024	0.029	0.036	0.017	0.024	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.002	0.007	0.012	0.000	0.002	0.000	0.000
6	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

(c) Summer

Lead time	Forecast origin rainfall category (upper limit) mm hr^{-1}											
hr	0	0.1	0.5	1	2	4	6	8	10	12	16	40
1	0.000	0.008	0.049	0.208	0.409	0.677	1.063	1.438	2.250	2.000	2.250	6.000
2	0.000	0.000	0.019	0.041	0.083	0.172	0.213	0.261	0.300	0.292	0.300	1.032
3	0.000	0.000	0.000	0.013	0.024	0.035	0.040	0.045	0.048	0.050	0.068	0.216
4	0.000	0.000	0.000	0.000	0.000	0.007	0.011	0.016	0.016	0.020	0.020	0.042
5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.013
6	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

8.4 CONDITIONING ON STORM TYPE

The previous sections have introduced the theory of conditional forecasting and illustrated application of the method based on annual, seasonal and monthly transition probability matrices. In practice a particular type of event can be recognised at the time of forecasting, for example when it is known that convective storms are likely. It is therefore of interest to impose conditioning on the event type in calculating the transition probabilities.

Choice of event type for conditioning

The choice of type of event has been resulted in consideration of three broad categories of storm event based on different durations and intensities. These are:-

(a) Events of any duration and intensity, where an event is defined as a period of time when rainfall occurs.

(b) Events of a given duration, with at least one hour in each event having rainfall above a given intensity.

(c) As (b) except that the events are chosen to be <u>within</u> a given duration, and not a fixed duration.

Forecasts are made for a lead time of 6 hours, but curtailed by the end of each event. This means for case (a) and (c), with variable duration storms, the number of forecasts associated with each lead time is variable. This fact should be noted, since in a later comparison of different forecast models there is only comparability across models at a given lead time and not of errors across lead times.

Evaluation of Forecasting models

It is of interest to compare the performance of the event-conditional forecasts with the yearly, monthly, seasonal and persistence forecasting models employed in the previous section. The inclusion of event-conditional models has led to a reconsideration of the rainfall intensity categories used as state variables in the forecasting scheme. The categories have been reduced from 12 (Table 8.2.1) to 8 and are set out in Table 8.4.1. The results obtained using this revised categorisation of rainfall are described next under the three broad event categories identified above.

(a) Events of a given duration and intensity

Probability transition matrices have been calculated using data only from storm events of a given duration and intensity. The specific duration/intensity events considered are 2h,3mm/h, 2h,5mm/h, 3h,5mm/h, 4h,3mm/h, 6h,1mm/h, and 12h,1mm/h. Forecast matrices have been calculated for each of these six event types and used as

Table 8.4.1 Rainfall categorisation

Category	Rainfall rate (upper limit) mm hr^{-1}	Rainfall value assigned mm hr^{-1}
1	0.1	0.05
2	0.5	0.3
3	1	0.75
4	2	1.5
5	4	3
6	8	5
7	16	12
8	40	28

the basis of forecasting. The rms log-error statistics for a lead times up to 6 hours are presented in Table 8.4.2 along with comparable error statistics obtained from yearly, seasonal, monthly and persistence models. For each of these models the same event data are used to allow direct comparison between models for a given lead time; the number of errors making up the error statistics is indicated at the foot of each table. The event model always outperforms the other models with the yearly model often giving the second best set of forecasts, especially at lower lead times. It is seen that the naive persistence forecast is always worst, except at short lead times in the events of 12 hour duration.

(b) Events within a given duration and above a given intensity

The performance statistics are presented in Table 8.4.3 along with those obtained from the alternative models. In general the event-conditional model outperforms the others. The persistence model is always bettered except for a one hour lead time for events of 12 hours duration or less, and also in the case of 2 hour events or less, where the intensity must be at least 5mm h^{-1} for one hour of the event.

(c) Events of any duration and intensity

Table 8.4.4 (a) shows the performance statistics obtained in this case. In addition to the yearly, seasonal, monthly and persistence model results the performance of the 6h,1mm/h event-conditioned model is shown; this model performed well overall in the assessment up to now. Note that the statistics are calculated over events of any duration and intensity and that in this case the yearly model is equivalent to the event-conditioned model of any duration and intensity. The yearly model is best for a lead time of one hour, but the 6hr,1mm h^{-1} event-conditioned model subsequently outperforms the other models. A persistence forecast is always worst except at a one hour lead time.

Table 8.4.2 ***Performance statistics for different event-conditional forecast models: events of a given duration case. Persistence, season, month and year model performance statistics are given for comparison purposes. Performance statistic is root mean square log-error***

a) 2 h, 3 mm h^{-1}

	Lead time, hrs					
	1	2	3	4	5	6
Persistence	1.429^{5}					
Event	0.692^{*}					
Month	1.045^{3}					
Season	1.167^{4}					
Year	0.997^{2}					
	27					

b) 4 h, 3 mm h^{-1}

	Lead time, hrs					
	1	2	3	4	5	6
Persistence	1.045^{5}	1.214^{5}				
Event	0.734^{*}	0.822^{*}				
Month	0.845^{3}	0.945^{4}				
Season	0.912^{4}	0.935^{3}				
Year	0.794^{2}	0.894^{2}				
	60	60				

c) 2 h, 5 mm h^{-1}

	Lead time, hrs					
	1	2	3	4	5	6
Persistence	1.557^{4}					
Event	0.748^{*}					
Month	1.542^{3}					
Season	1.726^{5}					
Year	1.373^{2}					
	10					

d) 3 h, 5 mm h^{-1}

	Lead time, hrs					
	1	2	3	4	5	6
Persistence	1.480^{5}	1.697^{5}				
Event	0.033^{*}	0.033^{*}				
Month	0.168^{3}	0.168^{3}				
Season	0.047^{2}	0.044^{2}				
Year	0.577^{4}	0.287^{4}				
	5	5				

e) 6 h, 1 mm h^{-1}

	Lead time, hrs					
	1	2	3	4	5	6
Persistence	0.595^{5}	0.749^{5}	0.785^{5}			
Event	0.468^{*}	0.510^{*}	0.513^{*}			
Month	0.529^{3}	0.591^{3}	0.592^{4}			
Season	0.590^{4}	0.594^{4}	0.572^{2}			
Year	0.474^{2}	0.552^{2}	0.581^{3}			
	363	363	363			

f) 12 h, 1 mm h^{-1}

	Lead time, hrs					
	1	2	3	4	5	6
Persistence	0.432^{3}	0.578^{4}	0.661^{5}	0.701^{5}	0.726^{5}	0.738^{5}
Event	0.358^{*}	0.430^{*}	0.492^{*}	0.510^{*}	0.518^{*}	0.522^{*}
Month	0.446^{4}	0.581^{5}	0.586^{4}	0.586^{4}	0.586^{3}	0.586^{2}
Season	0.567^{5}	0.563^{3}	0.553^{2}	0.571^{2}	0.581^{2}	0.586^{2}
Year	0.386^{2}	0.510^{2}	0.558^{3}	0.578^{3}	0.586^{3}	0.586^{2}
	348	348	348	348	348	348

Table 8.4.3 Performance statistics for different event-conditional forecast models: within event case. Persistence, season, month and year model performance statistics are given for comparison purposes. Performance statistic is root mean square log-error.

a) 2 h, 3 mm h^{-1}

	Lead time, hrs					
	1	2	3	4	5	6
Persistence	1.429^{5}					
Event	0.692*					
Month	1.045^{3}					
Season	1.167^{4}					
Year	0.997^{2}					
	27					

b) 4 h, 3 mm h^{-1}

	Lead time, hrs					
	1	2	3	4	5	6
Persistence	1.485^{5}	1.166^{2}	1.029^{5}			
Event	0.772*	0.721*	0.494*			
Month	0.948^{3}	0.809^{3}	0.565^{3}			
Season	1.028^{4}	0.817^{4}	0.568^{4}			
Year	0.884^{2}	0.779^{2}	0.549^{2}			
	171	87	30			

c) 2 h, 5 mm h^{-1}

	Lead time, hrs					
	1	2	3	4	5	6
Persistence	1.557^{4}					
Event	0.748*					
Month	1.542^{3}					
Season	1.726^{5}					
Year	1.373^{2}					
	10					

d) 3 h, 5 mm h^{-1}

	Lead time, hrs					
	1	2	3	4	5	6
Persistence	1.547^{5}	1.697^{5}				
Event	0.977*	1.029^{4}				
Month	1.276^{3}	0.057^{2}				
Season	1.428^{4}	0.044*				
Year	1.196^{2}	0.287^{3}				
	20	5				

e) 6 h, 1 mm h^{-1}

	Lead time, hrs					
	1	2	3	4	5	6
Persistence	0.694^{5}	0.765^{5}	0.750^{5}	0.711^{5}	0.547^{5}	
Event	0.548*	0.521*	0.462*	0.435*	0.272^{3}	
Month	0.633^{3}	0.616^{4}	0.544^{4}	0.492^{4}	0.265*	
Season	0.658^{4}	0.605^{3}	0.510^{2}	0.475^{2}	0.296^{4}	
Year	0.585^{2}	0.586^{2}	0.534^{3}	0.491^{3}	0.265*	
	1878	1268	757	370	121	

f) 12 h, 1 mm h^{-1}

	Lead time, hrs					
	1	2	3	4	5	6
Persistence	0.571^{3}	0.664^{5}	0.692^{5}	0.696^{5}	0.690^{5}	0.675^{5}
Event	0.501*	0.532*	0.518*	0.499*	0.468*	0.434*
Month	0.578^{4}	0.619^{4}	0.596^{4}	0.570^{4}	0.534^{4}	0.493^{3}
Season	0.616^{5}	0.604^{3}	0.560^{2}	0.554^{2}	0.520^{2}	0.489^{2}
Year	0.518^{2}	0.575^{2}	0.579^{3}	0.566^{3}	0.533^{3}	0.493^{3}
	5531	4468	3504	2664	1962	1388

Table 8.4.4 Performance statistics for events of any duration and intensity. The 6 hr, 1 mm h^{-1} event-conditioned forecast model (within event case) is compared here with persistence, season, month and year models. Statistics are also given obtained from the 75% and 90% forecast matrices in addition to the best estimate (50% risk level). Performance statistic is root mean square log-error.

a) 50% risk level

	Lead time, hrs					
	1	2	3	4	5	6
Persistence	0.378^{3}	0.472^{5}	0.514^{5}	0.538^{5}	0.553^{5}	0.566^{5}
Event 6 hr, 1mm h^{-1}	0.375^{2}	0.402*	0.410*	0.416*	0.416*	0.415*
Month	0.402^{4}	0.465^{4}	0.475^{4}	0.480^{4}	0.481^{3}	0.481^{3}
Season	0.452^{5}	0.454^{3}	0.467^{3}	0.470^{2}	0.471^{2}	0.477^{2}
Year	0.354*	0.429^{2}	0.459^{2}	0.476^{3}	0.481^{3}	0.481^{3}
	18395	13799	10641	8261	6415	4987

b) 75% risk level

	Lead time, hrs					
	1	2	3	4	5	6
Persistence	0.378^{3}	0.472^{4}	0.514^{4}	0.538^{4}	0.553^{4}	0.566^{4}
Event 6 hr, 1mm h^{-1}	0.575^{5}	0.594^{5}	0.600^{5}	0.601^{5}	0.600^{5}	0.599^{5}
Month	0.352^{2}	0.400^{2}	0.440^{2}	0.464^{3}	0.472^{3}	0.474^{3}
Season	0.452^{4}	0.450^{3}	0.461^{3}	0.463^{2}	0.464^{2}	0.469^{2}
Year	0.343*	0.382*	0.395*	0.405*	0.411*	0.413*
	18395	13799	10641	8261	6415	4987

c) 90% risk level

	Lead time, hrs					
	1	2	3	4	5	6
Persistence	0.378*	0.472*	0.514^{3}	0.538^{3}	0.553^{3}	0.566^{3}
Event 6 hr, 1mm h^{-1}	0.826^{5}	0.858^{5}	0.871^{5}	0.872^{5}	0.872^{5}	0.841^{5}
Month	0.574^{4}	0.560^{4}	0.509^{2}	0.479*	0.463*	0.456*
Season	0.472^{3}	0.484^{2}	0.499*	0.504^{2}	0.505^{2}	0.510^{2}
Year	0.463^{2}	0.542^{3}	0.556^{4}	0.563^{4}	0.567^{4}	0.567^{4}
	18395	13799	10641	8261	6415	4987

The following general conclusions can be drawn from the overall model evaluation results:

(i) the monthly and seasonal models perform poorly;

(ii) the yearly model performs fairly well, especially at shorter lead times;

(iii) an event-conditioned model in general outperforms other models.

The reason for the poor performance of the monthly and seasonal models may reflect that certain weather conditions are not confined to particular months or seasons; it may also reflect less reliable estimation of the probability transition matrices from fewer data samples.

Risk Level Forecasting

A particularly valuable feature of the conditional forecasting methodology is that, in addition to the forecast value corresponding to a 50% probability of non-exceedence, "forecasts" corresponding to other risk levels can be calculated based on equation (8.2.3). This has obvious advantages for flood warning. Table 8.4.4 (b) and (c) present the rms log-error values obtained for the 75% and 90% non-exceedence risk levels. Clearly, these will, and do, provide poorer forecasts. However, they do provide a means of establishing a statistically-based assessment of flood risk.

The corresponding forecast matrices used to derive these risk estimates are shown in Table 8.4.5 for the 6h, 1 mm h^{-1} within duration case. The forecast matrices for the yearly (unconditional) model are shown in Table 8.4.6 and Figure 8.4.1 for the purposes of comparison and also because this model performs reasonably well across all types of event. It is seen that whilst the 50%-risk forecast matrix always will forecast a lower rainfall than the current rainfall, irrespective of lead time, the 90%-risk forecast matrix will lead to increases in forecast rainfall, at least when the current rainfall rate is small.

8.5. SUMMARY AND FURTHER WORK

A simple method of conditional rainfall forecasting based on Markov chains has been developed and trials undertaken using the Hampton hourly rainfall record. The assessment, has formally evaluated the relative merits of non-seasonal, seasonal and monthly Markov chain models. In addition, probability transition matrices have been calculated using events of specified type, in terms of duration and intensity. The resulting event-conditioned forecasting models have performed best. However, the fairly good performance of the yearly model under all conditions means that it provides a resilient model in the practical forecasting situation where storm intensity and duration are unknown. Particularly in convective situations the event-conditioned

Table 8.4.5 Forecast matrices for different risk levels corresponding to Table 8.4.3(c) 6h, 1 mm h^{-1} within event case.

(a) 50% risk level

Lead time	Forecast origin rainfall category (mid value) mm hr^{-1}							
hr	0.05	0.3	0.75	1.5	3	5	12	28
1	0.145	0.459	0.767	0.239	0.423	0.414	1.314	0.175
2	0.248	0.268	0.271	0.282	0.296	0.295	0.319	0.459
3	0.265	0.271	0.273	0.269	0.271	0.274	0.282	0.268
4	0.268	0.269	0.269	0.270	0.270	0.269	0.271	0.271
5	0.269	0.269	0.269	0.269	0.269	0.269	0.270	0.269
6	0.269	0.269	0.269	0.270	0.269	0.268	0.270	0.269

(b) 75% risk level

Lead time	Forecast origin rainfall category (mid value) mm hr^{-1}							
hr	0.05	0.3	0.75	1.5	3	5	12	28
1	0.875	1.231	1.306	0.859	1.154	1.442	2.818	0.238
2	1.048	1.070	1.065	1.120	1.146	1.153	1.168	1.231
3	1.077	1.091	1.096	1.083	1.087	1.093	1.117	1.070
4	1.084	1.085	1.085	1.089	1.087	1.085	1.090	1.091
5	1.085	1.086	1.086	1.088	1.086	1.084	1.089	1.085
6	1.086	1.086	1.086	1.089	1.086	1.084	1.088	1.086

(c) 90% risk level

Lead time	Forecast origin rainfall category (mid value) mm hr^{-1}							
hr	0.05	0.3	0.75	1.5	3	5	12	28
1	1.426	2.139	2.226	1.563	2.452	3.589	4.662	0.275
2	1.753	1.906	1.921	1.952	2.057	2.170	2.348	2.139
3	1.871	1.911	1.924	1.911	1.919	1.933	2.015	1.906
4	1.896	1.903	1.906	1.918	1.907	1.896	1.930	1.911
5	1.904	1.906	1.908	1.920	1.905	1.891	1.921	1.903
6	1.908	1.909	1.910	1.923	1.908	1.893	1.921	1.906

Table 8.4.6 Forecast matrices for different risk levels for yearly (unconditional) case.

(a) 50% risk level

Lead time	Forecast origin rainfall category (mid value) mm hr^{-1}							
hr	0.05	0.3	0.75	1.5	3	5	12	28
1	0.050	0.132	0.273	0.518	0.833	1.257	2.250	4.514
2	0.050	0.067	0.163	0.224	0.283	0.397	0.605	1.095
3	0.050	0.050	0.092	0.130	0.164	0.196	0.246	0.327
4	0.050	0.050	0.050	0.072	0.094	0.114	0.148	0.195
5	0.050	0.050	0.050	0.050	0.051	0.064	0.086	0.119
6	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.069

(b) 75% risk level

Lead time	Forecast origin rainfall category (mid value) mm hr^{-1}							
hr	0.05	0.3	0.75	1.5	3	5	12	28
1	0.050	0.319	0.710	1.186	1.691	2.710	4.607	16.036
2	0.149	0.330	0.598	0.787	1.041	1.297	1.906	3.607
3	0.205	0.294	0.462	0.571	0.667	0.770	1.023	1.481
4	0.234	0.283	0.356	0.425	0.490	0.550	0.650	0.856
5	0.250	0.276	0.296	0.326	0.370	0.407	0.477	0.584
6	0.259	0.273	0.285	0.291	0.298	0.313	0.360	0.433

(c) 90% risk level

Lead time	Forecast origin rainfall category (mid value) mm hr^{-1}							
hr	0.05	0.3	0.75	1.5	3	5	12	28
1	0.252	0.883	1.336	2.077	2.794	4.880	9.000	23.243
2	0.519	1.056	1.343	1.584	2.161	2.712	4.339	14.937
3	0.691	1.051	1.255	1.365	1.476	1.830	2.436	4.330
4	0.794	1.024	1.167	1.233	1.309	1.376	1.553	2.340
5	0.885	1.002	1.101	1.137	1.189	1.225	1.318	1.480
6	0.934	0.989	1.060	1.074	1.111	1.125	1.187	1.290

50% risk *75% risk* *90% risk*

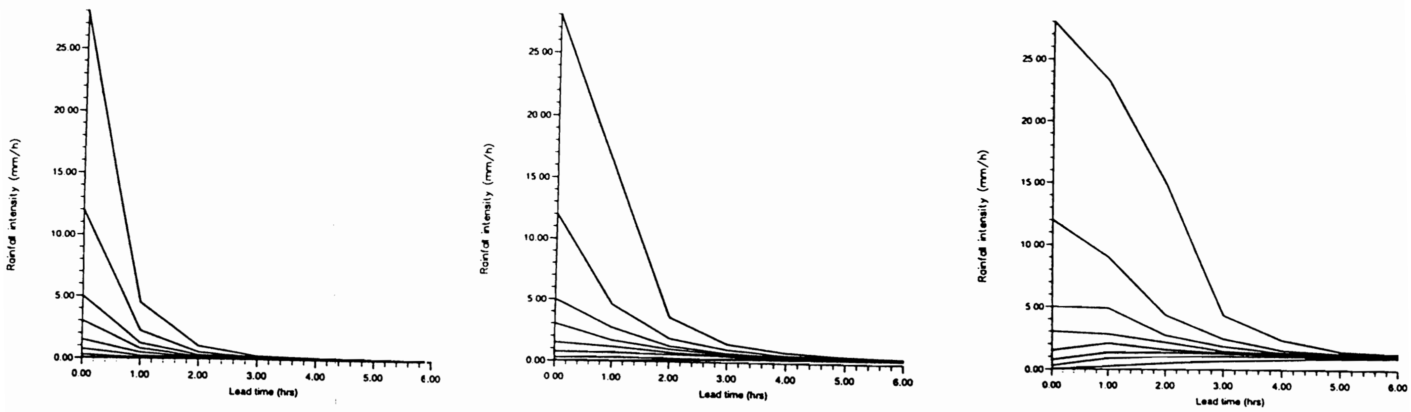


Figure 8.4.1 ***Risk-based forecast rainfall rate against forecast lead time conditional upon rainfall rate at the forecast origin : yearly model.***

forecasts for high intensity, short duration storms provide a valuable complement to the more resilient yearly model forecasts.

An advantage of the conditional forecasting approach has been shown to be its ability to produce risk-based forecasts, in addition to the usual 50% probability of non-exceedence forecast. This is seen to be particularly relevant to risk-based flood warning.

An extension to consider forecasting sub-hourly rainfall amounts, in particular 15 minute totals used operationally in flood forecasting models, has been considered. However, the nature of the PEPR dataset means that time series of 15-minute rainfall totals are difficult to derive with any reliability. It is recommended that an assessment of the conditional forecasting approach using a 15-minute basic time interval be based on data other than the PEPR dataset. This work is outside the scope of the present study.

9. Summary, conclusions and suggestions for further work

The Precision Encoder and Pattern Recognition System (PEPR) raingauge dataset for London has been found to contain records for 77 raingauges, extending over variable length periods ending in 1976. Whilst the majority of records are less than 20 years, two extend for considerably longer: that for Hayes begins as early as 1928, but suffers a break in record from 1945 to 1960, and that for Hampstead begins in 1933. The latter two records have been analysed more extensively in the present study. A database for the PEPR dataset has been created at IH to support analysis. In addition, a PC database has been developed and supplied for use by the National Rivers Authority.

Quality control of the data, reported more extensively in the report's Appendix, has revealed serious shortcomings in the dataset. Missing data together with an anomalous number of dry months in many of the records has meant that analyses involving the inference of storm return period be treated with a degree of circumspection. Also, the data are such that rainfall totals for specified periods less than one hour are imprecisely defined, making depth-duration-frequency analyses impractical for durations of less than one hour.

A broad look at the data was achieved through the construction of seasonal data tables, reported for Hayes and Hampstead in Section 3, but recorded for all 77 raingauge stations in an Annex to this report. Three tables were prepared for each gauge record, concerning total rainfall, maximum hourly rainfall and the proportion of days without missing data. These tables were supplemented by graphical displays designed to expose any temporal patterns in rainfall over time and with season. Missing data displays were constructed so as to clarify the extent of missing data and any tendency to occur concurrently at different sites in order to assess their likely impact on subsequent return period analyses. These analyses revealed that, whilst the pattern of monthly rainfall is fairly uniform throughout the year, more extreme hourly rainfall amounts tend to occur in the months of July and August. The importance of short duration summer storms needs to be taken into consideration in the design of storm drainage facilities for London. Visual inspection of time series plots of rainfall maxima suggest little evidence of behaviours that are anything but random.

Of particular interest has been any evidence in the PEPR dataset that might point to preferential areas of storm development over London which might have implications for storm drainage design. A set of 15 notable storm events have been examined by obtaining isohyetal maps of daily rainfall for each storm, derived using the PEPR network of raingauges and a multiquadric rainfall interpolator. These, together with a map of gauges giving the maximum daily total for each storm, failed to highlight any area of London particularly prone to extreme storms. However, an analysis of the storm profiles for these 15 storms revealed a variety of shapes with bimodal (double-peaked) profiles not being uncommon. The symmetric storm profiles, commonly assumed in design calculations, are not characteristic of the 15 profiles observed here.

There is a growing awareness of the limitations of the design storm approach to drainage design and increasing acceptance of a continuous simulation approach involving rainfall time series, possibly stochastically generated. Often as the basis of the rainfall simulation a rainfall time series is characterised by features such as the depth of a wet spell, the durations of wet and intervening dry spells and some description of the shape of the storm profile. It has not been the purpose of the current report to develop a rainfall simulation model but rather to use the characteristics that might feature in such a model as the basis of investigating possible spatial patterns in their variation over London. The depth and durations have been regarded as random variables and the following four distributions considered as potential candidates: exponential, lognormal, Gamma and generalised Pareto. The parameters of these distributions, along with the inferred mean and standard deviation, have been estimated from each raingauge record and mapped over London using the multiquadric interpolator. It has been difficult to draw any general conclusions from these maps other than that spatial patterns of variability are apparent for the different storm characteristics; however, no tests of significance have been carried out. On average, the maps suggest shorter duration, heavier storms in the east and longer duration, lighter storms to the north-west and south of London. An analysis of storm profiles, characterised by beta distributions, for Hayes and Hampstead suggest that shorter duration storms have the most symmetric profiles and those of longer duration tend to rise steeply and fall more gradually. A correlation analysis of within-storm rainfall served to quantify the significant serial correlation of hourly rainfall totals.

With the reservations expressed above on the use of the PEPR dataset for return period analyses, Section 6 presents a classical depth-duration-frequency (DDF) analysis for durations of 1, 2, 4, 6, 12, 24 and 48 hours. Only records with at least 75% of data in any year being present and with a minimum record length of 5 years have been used: this restricted the analysis to 35 gauges. Generalised Extreme Value distributions were fitted to each gauge record using probability weighted moments and the distributions used to infer the rainfall depth having a given depth and duration. Isohyetal maps for London were constructed from these using a multiquadric interpolator. No consistent overall pattern was evident for the various durations and return periods examined. Average DDF curves have been obtained from the 35 gauges, along with site curves for Hayes and Hampstead.

Extension of the DDF analysis to sub-hourly durations was not possible because of the way rainfall are recorded within the hour in the PEPR dataset. However, the classic analysis of Bilham concerned with maximum rainfall depths falling within a given duration can be reproduced using the PEPR dataset. This has been undertaken in Section 7 and leads to a broad confirmation of the validity of the Bilham formula, in its revised form, for London and the development of a modified form of it. However, it is recommended that design should follow the Flood Studies Report procedures which concern return period estimates of storms of given depth and duration.

Section 8 has dealt with an operational application of the PEPR dataset to forecast short-term rainfall by a Markov chain procedure. The method is based on a consideration of rainfall quantised into n intensity classes and the assumption that given the rainfall over the last, say, 1 hour a transition matrix can be calculated giving the probability of rain in any of the n classes in the next hour. This forms the basis of a rainfall forecasting method to estimate rainfall over several future intervals and also the risk of higher rainfall amounts occurring. The procedure might be of value for flood warning, possibly in conjunction with a rainfall-runoff model. A range of variants to the basic form of Markov structure have been investigated, in which the transition matrix may vary with month, with season or with storm type. In general, the basic form of model provides the most resilient forecasts overall although there may be some merit in choosing an event-type conditioned transition matrix for forecasting convective storms.

The main conclusions deriving from the study of Rainfall Patterns over London are summarised below:

(i) The PEPR data set is not readily analysed and careful quality control and the development of software checks are required before routine analyses can be undertaken. This has resulted in the IH database which contains a number of safeguards against misuse of the data set together with Annex A which provides further information on its reliability.

(ii) Most of the PEPR data are available only for the 20 years ending 1976, although two long records exist: at Hayes from 1928; with a gap of 16 years, and at Hampstead from 1933.

(iii) Extreme hourly rainfalls show a tendency to occur in summer during July and August. This has important implications on the design of culverts and the engineering works in the London area.

(iv) Monthly rainfall totals tend to be fairly uniform throughout the year.

(v) Based on a simple visual analysis, temporal variations in hourly rainfall maxima do not seem to exhibit a behaviour that is anything but random.

(vi) Mapping of gauge daily maxima for notable storm events does not provide evidence for preferential locations for extreme rainfalls over London.

(vii) A multiquadric surface fitting approach provides an automatic means of deriving isohyetal maps of storm rainfall.

(viii) Storm profiles exhibit significant variety in shape and double-peaked (bimodal) profiles are not uncommon.

(ix) Characterisation of rainfall time series into wet and dry spells, and the fitting of distributions to storm features, such as wet period duration, magnitude and shape, provide a useful framework within which to examine rainfall variability in space.

(x) Maps of distribution parameters reveal shorter duration, heavier storms in the east and longer duration, lighter storms to the north-west and south of London, on average.

(xi) Shorter duration storms tend to have the most symmetric profiles whilst those for longer durations tend to rise steeply and fall more gradually.

(xii) The dependence between adjacent hourly rainfall values is significant.

(xiii) Isohyetal maps of rainfall of a given duration and return period can be derived through fitting GEV distributions to single-site data and using a multiquadric surface interpolation method in support of the map derivation. The value of these maps must be weighed against the presence of missing data in the data set used in their derivation. No overall consistent pattern in rainfall extremes emerged from this analysis.

(xiv) Depth-duration-frequency curves for Hampstead and Hayes and as an average for 35 gauges have been derived for durations of 1, 2, 4, 6, 12 and 24 hours.

(xv) An analysis similar to that used by Bilham in 1935 involving counting the proportion of days with rainfall of a given depth and duration has yielded results which are broadly consistent to those of Bilham for the London area. However, procedures contained in the Flood Studies Report based on the return period of storms of a given depth and duration should be used for design, and not the Bilham method.

(xvi) An operational application of the PEPR dataset for conditional rainfall forecasting has been developed based on Markov chain theory. This provides a simple rainfall forecasting method and also allows the risk of exceedence to be established. The latter might provide the basis of a risk-based flood warning.

Recommendations for further work must be moderated in the light of the shortcomings of the PEPR dataset, particularly for analyses involving sub-hourly rainfall amounts and frequency of occurrence. With this reservation the following opportunities are put forward:

(i) Development of a stochastic rainfall model for generating time series of rainfall for use in a continuous simulation approach to urban storm drainage design, extending the work on storm characterisation reported in Section 5.

(ii) Extension of (i) to consider a space-time model of rainfall fields for design use.

(iii) Use of the PEPR dataset to investigate how the magnitude of rainfall varies with area. The opportunity exists to develop areal adjustment factor relations to adjust point rainfall estimates for different catchment areas as a function of storm duration.

(iv) Application of the conditional rainfall forecasting method to 15 minute rainfall time series from the NRA Thames Region telemetry database to derive a simple rainfall forecasting scheme for operational use for flood warning. This would involve deriving forecast matrices for selected gauge sites in the Thames Region, a quite straightforward task using the methodology and software developed for the present project. An assessment in a flood forecasting context, along with local radar rainfall forecasts, might also be undertaken.

(v) Analysis of rainfall patterns over London using, instead of the PEPR dataset, the 15 minute telemetry raingauge archive for the Thames Region complemented by data from the London Weather Radar.

Appendix A Quality control of PEPR data

A1. Introduction

The apparent very frequent occurrence of missing data in the PEPR records raised serious concerns regarding their validity during the course of the Study. This Appendix describes an investigation into this problem and the results found in a partial quality control of the database, through comparison with original microfiche charts.

A2. Microfiche analysis for Bury Farm

An initial review of the validity of PEPR data was carried out using rainfall records for Bury Farm (237162) for the years 1972 and 1973. Comparison of microfiche charts with daily totals from the PEPR database indicate that for periods designated as missing in the PEPR dataset, the microfiche exists, but the rainfall was zero. Conversely a dry period in the PEPR dataset had no corresponding microfiche copy. The original data, supplied on magnetic tape by the NRA Thames Region, had been decoded in the following three ways:

(i) "wet" days with a header (date, time, etc) followed by data;
(ii) "dry" days with a header followed by no data; and
(iii) "missing" days with no header or data.

However, closer examination of documentation on the PEPR dataset, obtained after the database had been set up at IH, revealed that 'Archived data contains only "downpours"..., all dry periods are not stored', where "downpours" here refers to any wet periods. Given this statement and the above inconsistencies between PEPR and microfiche data during dry and missing periods it was decided to modify the decoding. Periods with headers alone (case (ii)) would be considered "missing" and periods with no header or data (case (iii)) would be considered "dry". These rules apply only within the limits of the dates given in the original listing of available gauge data; outside these limits the data are obviously "missing".

A3. Seasonal analysis

The seasonal analysis, described in Section A2, is used here to examine the offset of the revised decoding. This revealed some serious inconsistencies within the data. For a number of stations there are periods when monthly totals are zero: the extent of the problem is illustrated in Tables A.3.1 and A.3.2. Tables A.3.3 and A.3.4 list the corresponding totals given in 'Weather' along with a description of the general weather conditions: these serve to confirm the spurious nature of the zero monthly totals. Clearly, whilst the modified decoding has reduced the occurrence of missing data it has had the adverse effect of introducing spurious dry days into the record. The next section considers the introduction of a "suspect" code to flag data as being of dubious reliability.

A4. Introduction of a "Suspect" code

A "Suspect" code has been introduced into the PEPR database software to gain stronger control over the likely reliability of retrieved data. The code is used to inform the user of certain characteristics of the data, providing a means of ignoring selected data if so desired. The following suspect codes have been assigned:

(a) -1: Data are missing on this day

(b) 0: Data for the day are reliable

(c) 1: Start time after stop time. Often start and stop amounts are not recorded exactly at 24 hour intervals and so this can easily occur if a reading is taken more than 24 hours after the previous one. It is not considered to be an important problem.

(d) 2: Start amount greater than stop amount. Again this does not really indicate a problem with the data. In periods of intense rainfall the pen can easily reach the top of the chart and reset itself. The start and stop amounts indicate where the pen started and finished on the chart and not start and stop amounts of cumulative rainfall.

(e) 3: If stop amounts are greater than start amounts, but cumulative amounts are zero.

Table A.3.1 **_Green Lanes (245291): monthly totals (mm)/ percentage of data present_**

Year	January	February	March	April
1963	Missing	Missing	0.0/03	16.1/30
1964	Missing	Missing	0.0/23	47.9/43
1965	Missing	Missing	0.0/19	0.5/27
1966	Missing	Missing	0.0/23	0.8/17
1967	Missing	Missing	0.0/32	0.0/17
1968	Missing	0.0/34	0.0/06	39.8/90
1969	Missing	Missing	Missing	2.5/17
1970	Missing	Missing	Missing	22.1/33
1971	Missing	Missing	Missing	0.0/07

Table A.3.2 **_Chandos Recreation Ground (246738): monthly totals (mm)/percentage of data present_**

Month	1957	1958	1959	1960
January	35.5/100	34.9/84	0.0/65	0.0/58
February	44.1/96	13.8/75	0.0/93	0.0/45
March	32.4/100	20.8/94	0.0/29	0.0/68
April	4.1/93	3.0/80	0.0/47	0.0/67
May	24.4/97	0.0/45	1.3/84	0.0/71
June	12.4/97	0.0/43	0.0/63	0.0/57
July	60.0/94	0.0/45	0.0/65	0.0/29
August	40.0/94	0.0/39	0.0/71	11.6/61
September	28.4/93	0.0/53	0.0/93	95.3/97
October	16.4/84	0.0/55	0.0/58	136.4/90
November	26.9/93	0.0/57	0.0/47	93.9/90
December	33.4/94	0.0/39	0.0/16	78.4/94

Table A.3.3 ***Months with zero rainfall in PEPR dataset and corresponding weather description and monthly rainfall at Kew: 1963-1971***

Date	General weather description	Monthly rainfall at Kew (mm)
March 1962	Very wet	59
March 1964	Generally cold, dull and wet	83
March 1965	Very cold at first, very warm later	46
March 1966	Mostly mild, dry in south and east	11
March 1967	Generally mild	36
April 1967	Changeable	48
February 1968	Cold	24
March 1968	Dry in the south	23
April 1971	Generally dull, dry and cool	36

(f) 7: Hourly amounts indicate zero rainfall over a day, but cumulative amounts indicate non-zero amounts.

(g) 8: All 24 hourly amounts equal zero, there are non-zero cumulative rainfall amounts given, and these reset themselves during the day. It has been found that in these circumstances the data are highly dubious.

The addition of a suspect code has allowed some questionable data to be ignored during analysis. In the work described here only suspect codes of -1 and 8 are considered to be a problem.

A5. Assessment using Microfiche data

In order to gain a fuller understanding of the problems described above, microfiche and PEPR data from five gauges were examined in greater detail. The results are summarised for each gauge in turn.

Table A.3.4 Months with zero rainfall in PEPR dataset and corresponding weather description and monthly rainfall at Kew: 1957-1960

Date	General weather description	Monthly rainfall at Kew (mm)
May 1958	Frequent thunderstorms, cool	68
June 1958	Dull, very wet	104
July 1958	Changeable	67
August 1958	Wet thundery, cloudy	83
Sept 1958	Changeable, heavy thundery rain	101
Oct 1958	Changeable at first then dry	51
Nov 1958	Changeable at first	48
Dec 1958	Variable with wet and foggy periods	75
Jan 1959	Snow, frost, floods, rain, sunny	54
Feb 1959	Extremely dry	2
March 1959	Mild, rather changeable, dull	136
April 1959	Changeable, wet, warm	52
June 1959	Warm, sunny	35
July 1959	Warm, sunny in England and Wales	40
Aug 1959	Dry, warm, mainly sunny	29
Sept 1959	Very dry, sunny and warm	3
Oct 1959	Warm and sunny, changeable later	48
Nov 1959	Mild and cloudy, wet in many places	60
Dec 1959	Mild, wet and stormy	79
Jan 1960	Cloudy and wet, severe snowstorms	43
Jan 1960	Sunshine and rain above average	42
March 1960	Mainly cloudy	40
April 1960	Changeable, then sunny and dry	40
May 1960	Mainly warm and dry	42
June 1960	Warm and mainly sunny	31
July 1960	Rather cool, cloudy and wet	86

(i) Bury Farm

Daily totals from the PEPR archive for Bury Farm (237162) for the years 1972 and 1973 were compared with microfiche check gauge readings. Days where differences occur are given in Table A.5.1.1 and the number of occurrences over these two years where the differences occur are shown in Table A.5.1.2.

Unless specified in Table A.5.1.2 and similar tables, the suspect code is not equal to 8. When the code is 8, then the PEPR data are counted as missing, in Table A.5.1.1. and others like it. Under "Comments" in these tables the following abbreviations are used:

(a) PEPR: This indicates some discrepancy between the PEPR daily total and the microfiche check gauge reading, with the PEPR value being more consistent with the trace itself.

(b) Microfiche: This is the same as in (a) except that the check gauge value is more consistent with the trace than the PEPR total.

(c) ?: This indicates that a significant inconsistency has occurred and that there is no obvious reason for it.

Also, where differences in rainfall totals between the PEPR data and the microfiche are of the order of 0.5mm or less, the data are said to be within acceptable error limits.

On the whole there is a good match between PEPR and microfiche data over the two years examined. Differences do occur, but are not a major cause of concern.

(ii) Green Lanes

A comparison was made between microfiche and PEPR data for Green Lanes raingauge (245291) for the period 1963 to 1971. It has already been shown (Section A3) that there are a concerning number of 'dry' periods occurring in the early parts of these years in the PEPR data. Closer examination of two years, 1963 and 1967, revealed the following. For 1963 the microfiche data are completely missing between 1 January and 18 April. The PEPR data are in agreement with this, apart from 31 March, when the day is given as dry, and not missing. The program which calculates monthly totals will compute a total so long as a month is not completely missing: hence, March 1963 is not given as missing, but as dry in the list of totals. There are no variables within the PEPR database which explain why this day should be different from the rest in this missing period and the microfiche also offers no clarification. In the other 'dry' months shown above, the situation is similar with odd days being given in the PEPR database as dry, when in reality the charts are completely missing. Even if it is valid to give these days as dry it gives a false impression of a month's rainfall in finding rainfall totals for that month.

Table A.5.2.1 shows days in 1963 and 1967 where rain/no rain/missing day inconsistencies occurred and Table A.5.2.2 shows the number of occurrences of such differences for these two years.

(iii) Hampstead

A comparison was made of microfiche and PEPR data for the Hampstead raingauge (246690) for the year 1941. On the whole there is a good correspondence between PEPR data and microfiche in terms of rain/no rain/missing days for Hampstead and also in terms of the closeness of the daily totals. Tables A.5.3.1 and A.5.3.2 indicate the differences found over this year.

(iv) Hampton 284152, 1959

A comparison between microfiche and PEPR data was made for the Hampton raingauge (284152) for the year 1959. The record for Hampton, at least from a superficial examination, appears to contain an ideal set of data. It is a 21 year record and the PEPR database contains none of the above 'dry' months or months which are explicitly given as missing. Comparison of microfiche data with PEPR data for 1959 reveals that PEPR daily totals are within 0.5mm of microfiche check gauge values for the whole year and that there is a perfect match between rain/no rain/missing days.

Tables A.5.4 show monthly totals, percentage of data present and maximum hourly values over the data record. Note the perfect match between the yearly total of monthly averages and the average of yearly totals, implying that the data set must be nearly all present. The percentage of data present for each month, on average over all years, indicates that 98-100% are present.

(v) Chandos Recreation Ground

The Chandos Recreation Ground (246738) record was examined for the years 1957 to 1960. Tables A.5.5.1 and A.5.5.2 describe rain/no rain/missing day inconsistencies up to the middle of April 1958. After this time, no reliable traces exist on the gauge charts and only bottle readings are given. This missing period lasted until August 1960, except for a day in May 1959 when both microfiche and PEPR data indicate identical falls of rain. As in the case of Green Lanes the cause of zeros appearing in monthly totals during this missing period is the result of 'dry' days being falsely implied in the PEPR record. However, whereas no charts existed at all for Green Lanes during its missing periods there are charts for this gauge, but they have only bottle readings on them. This made it possible to identify when a dry day might have occurred. A comparison of bottle readings with daily totals from the PEPR dataset (they were coded either -1 or 0 in this case) seems to imply that generally when the bottle reading is zero, PEPR data give a dry day and when the bottle reading is > 0, PEPR data give a missing day. Tables A.5.5.3 and A.5.5.4 list days where this rule does not apply. The number of such days is seen not to be significant, and so it may be concluded that on dry days PEPR data correctly gives a dry day, but that on wet days PEPR data are missing. It is doubtful whether the same line of reasoning can be applied to Green Lanes and its applicability to other gauges is uncertain.

Tables A.5.5.5 and A.5.5.6 describe rain/no rain/missing day inconsistencies from the middle of August 1960 up to the end of the year. Daily totals for these four and a half months indicate that there are only two days where the difference between PEPR and microfiche values are greater than 0.5mm (see Table A.5.5.7).

Table A.5.1.1 ***Differences between PEPR daily totals and microfiche check gauge readings for Bury Farm, 1972 and 1973***

Date	PEPR	Microfiche	SUSPECT	Comments
28/04/72	0.0	5.3	8	Missing
08/05/72	1.6	3.5	2	PEPR
14/05/72	2.1	2.5	2	Similar
03/06/72	0.0	4.6	8	Missing
18/07/72	1.6	1.7	0	Similar
22/07/72	0.0	1.8	8	Missing
29/10/72	0.3	0.2	0	Similar
30/10/72	0.0	0.1	0	Similar
10/11/72	0.0	1.5	8	Missing
18/11/72	0.0	0.3	2	Similar
27/11/72	0.9	0.6	0	Similar
30/11/72	0.0	0.4	8	Missing
08/12/72	10.5	13.3	0	PEPR
19/01/73	0.8	0.3	0	Similar
21/02/73	2.2	2.3	0	Similar
25/02/73	0.2	0.0	0	Similar
21/04/73	11.4	11.0	2	Similar
22/04/73	4.3	3.9	0	Similar
21/05/73	3.8	3.9	2	Similar
05/07/73	8.3	6.4	2	PEPR
18/07/73	1.3	1.5	0	Similar
20/08/73	0.0	0.1	0	Similar
29/08/73	0.0	0.4	0	Similar
18/09/73	5.7	6.0	0	Similar
20/09/73	44.7	44.4	0	Similar
21/09/73	2.8	3.0	0	Similar
15/10/73	6.3	7.3	2	PEPR
16/10/73	7.5	6.1	0	PEPR
10/12/73	1.1	4.2	0	PEPR
11/12/73	3.5	0.4	2	PEPR

Table A.5.1.2 ***Number of occurrences of differences between PEPR daily totals and microfiche check gauge readings for Bury Farm, 1972 and 1973.***

Difference	Number of occurrences
PEPR dry, microfiche rain, SUSPECT=8	5
Difference<0.5mm	18
Check gauge value different to PEPR total, but PEPR more consistent with trace.	7

***Table A.5.2.1a** Comparison of PEPR daily totals and trace changes (approx.), in mm when rain/no rain/missing periods are inconsistent: Green Lanes 1963*

Date	PEPR	Microfiche	SUSPECT	Comments
31/03/63	0.0	Missing	0	1/1-18/4 mis
27/04/63	0.0	2.8	0	??
27/05/63	0.0	1.3	0	??
06/06/63	0.0	0.4	0	Similar
17/07/63	0.0	0.4	0	Similar
19/08/63	0.0	1.8	8	Missing
23/09/63	0.0	3.8	0	??
03/10/63	0.0	1.5	0	??
16/10/63	0.0	0.5	0	Similar
19/10/63	0.0	0.5	8	Missing
21/10/63	0.0	1.3	0	??
30/10/63	0.0	10.0	0	??
04/11/63	1.1	0.0	2	??
08/11/63	0.0	0.5	8	Missing
09/11/63	0.0	2.8	8	Missing
10/11/63	0.0	5.8	8	Missing
13/11/63	0.0	0.3	0	Similar
15/11/63	0.0	0.3	0	Similar
25/11/63	0.0	Rain????	0	Mult. trace

Table A.5.2.1b ***Comparison of PEPR daily totals and trace changes (approx), in mm when rain/no rain/missing periods are inconsistent: Green Lanes 1967.***

Date	PEPR	Microfiche	SUSPECT	Comments
19-24/03/67	0.0	Missing	0	1/1-24/4 mis
28-31/03/67	0.0	Missing	0	1/1-24/4 mis
25/04/67	0.0	0.0	8	Missing
21/05/67	0.0	2.8	0	??
29/05/67	0.0	10.0	8	Missing
08/06/67	0.0	0.3	0	Similar
19/06/67	0.0	0.5	0	Similar
26/06/67	0.0	0.3	0	Similar
02/08/67	0.0	2.0	0	??
05/08/67	0.0	0.3	0	Similar
17/08/67	0.4	0.0	0	Similar
20/08/67	0.0	0.0	8	Missing
12/09/67	0.4	0.0	2	Similar
22/09/67	0.3	0.0	0	Similar
05/10/67	0.0	2.5	0	??
11/10/67	0.0	5.5	8	Missing
29/10/67	0.0	0.5	0	Similar
31/10/67	Missing	3.0	-1	??
02/11/67	0.0	1.3	0	??
26/11/67	0.2	0.0	0	Similar

Table A.5.2.2a ***Number of rain/no rain/missing day inconsistencies between PEPR and microfiche data: Green Lanes 1963***

Inconsistency	Number of occurrences
Microfiche missing, PEPR dry	1
Microfiche rain, > 0.5 PEPR dry	6
Microfiche zero, PEPR rain > 0.5	1
0 < Microfiche ≤ 0.5, PEPR dry	5
Microfiche>0.5, PEPR dry, SUSPECT=8	5
Trace confused by others on same chart	1

Table A.5.2.2b ***Number of rain/no rain/missing day inconsistencies between PEPR and microfiche data: Green Lanes 1967***

Inconsistency	Number of occurrences
Microfiche missing PEPR dry	10
Microfiche >0.5, PEPR dry, SUSPECT=8	2
Microfiche dry PEPR dry, SUSPECT=8	2
Microfiche>0.5mm PEPR dry	4
0 < Microfiche ≤ 0.5, PEPR dry	5
Microfiche dry, 0 < PEPR ≤ 0.5	4
Microfiche>0.5mm PEPR missing	1

Table A.5.3.1 ***Comparison of daily Totals (mm) from PEPR data and microfiche: Hampstead, 1941.***

Date	PEPR	Microfiche CG	SUSPECT	Comments
01/03/41	6.4	7.6	0	PEPR
02/03/41	0.4	0.8	0	Similar
21/03/41	0.9	0.8	0	Similar
23/03/41	0.4	0.6	0	Similar
03/04/41	4.6	4.4	0	Similar
18/04/41	15.4	13.3	0	??Microfiche
19/04/41	5.9	8.0	2	PEPR
21/05/41	0.2	0.3	0	Similar
23/05/41	1.2	1.1	2	Similar
09/06/41	40.6	40.4	2	Similar
25/07/41	7.9	8.1	0	Similar
26/07/41	8.1	7.9	2	Similar
30/07/41	0.0	Messy Tr., 7.1	8	Missing
04/08/41	16.0	16.1	0	Similar
07/08/41	4.8	4.4	1	Similar
08/08/41	4.4	4.8	2	Similar
22/08/41	0.6	0.2	0	Similar
23/08/41	25.8	26.2	2	Similar
02/11/41	Missing	1.2	-1	??
03/11/41	1.2	Missing	0	??
07/12/41	0.0	1.8	8	Missing
08/12/41	0.0	0.1	8	Missing
09/12/41	0.0	0.2	8	Missing
10/12/41	1.5	1.4	0	Similar
21/12/41	0.3	0.2	0	Similar
22/12/41	0.2	0.3	0	Similar

Table A.5.3.2 ***Differences between PEPR daily totals and microfiche check gauge values: Hampstead 1941***

Difference	Number of occurrences
Daily PEPR total-microfiche check gauge=0.1mm	7
Daily PEPR total-microfiche check gauge=0.2mm	5
Daily PEPR total-microfiche check gauge=0.4mm	5
Difference between PEPR daily total and microfiche check gauge value>1mm, but trace more consistent with PEPR	2
Difference between PEPR daily total and microfiche check gauge value>1mm, but trace more consistent with microfiche cg.	1
Difference>0.5mm, SUSPECT=8	2
Difference small, SUSPECT=8	2
PEPR missing Microfiche rain	1
PEPR rain Microfiche missing	1

There were four two day periods when the data may have been swapped around. These are:

1. 25/7/41 Microfiche check gauge=7.9mm, PEPR daily total=8.1mm
   26/7/41 Microfiche check gauge=8.1mm, PEPR daily total=7.9mm

2. 7/8/41 Microfiche check gauge=4.8mm, PEPR daily total=4.4mm
   8/8/41 Microfiche check gauge=4.4mm, PEPR daily total=4.8mm

3. 2/11/41 Microfiche missing, PEPR daily total=1.2mm
   3/11/41 Microfiche check gauge=1.2mm, PEPR missing.

4. 21/12/41 Microfiche check gauge=0.2mm, PEPR daily total=0.3mm
   22/12/41 Microfiche check gauge=0.3mm, PEPR daily total=0.2mm

(a) Total rainfall in mm

Rainfall Totals (mm). Station: 284152

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total	Mths
1954	26.2	51.9	44.7	6.7	43.9	108.0	57.4	85.7	43.4	45.2	84.7	48.8	646.5	12
1955	54.5	27.1	22.8	5.8	87.5	63.1	8.0	19.7	47.0	57.2	25.5	48.4	466.6	12
1956	92.7	5.7	12.7	26.2	4.4	46.7	130.8	67.5	52.8	46.6	11.0	69.2	566.3	12
1957	38.3	70.3	23.5	7.5	36.8	18.6	75.4	118.2	63.0	45.5	55.5	44.7	597.2	12
1958	48.7	54.4	27.1	25.8	59.5	90.7	58.8	78.3	85.8	50.2	45.1	66.7	690.9	12
1959	49.6	1.6	44.6	51.2	25.2	24.6	45.7	31.9	0.8	49.8	65.1	72.7	462.8	12
1960	46.2	42.2	38.8	15.4	47.5	42.7	94.1	61.3	56.8	138.5	93.0	50.2	726.6	12
1961	59.9	52.9	3.9	47.5	29.3	30.2	34.9	100.5	55.7	51.4	53.1	59.5	578.7	12
1962	67.8	9.8	33.1	37.7	45.6	7.9	53.4	51.7	65.0	54.3	47.9	29.8	503.9	12
1963	14.2	4.8	60.5	51.6	42.3	25.5	33.1	68.3	65.3	38.6	118.9	18.0	540.9	12
1964	16.5	19.0	83.0	77.6	50.2	105.0	21.7	34.1	13.3	27.3	35.7	34.0	517.3	12
1965	47.5	11.5	38.2	36.2	38.2	47.1	74.0	51.8	114.3	15.8	64.6	82.8	621.8	12
1966	34.1	64.6	10.9	78.2	48.6	64.3	72.9	81.0	27.8	89.9	36.2	68.6	677.0	12
1967	35.2	53.4	39.1	51.2	107.3	42.7	63.6	58.0	59.1	95.2	38.2	50.5	693.3	12
1968	52.6	27.6	24.3	54.5	74.0	57.5	74.2	65.3	133.3	60.6	45.1	83.8	752.6	12
1969	69.1	19.7	57.7	22.1	53.7	25.7	85.8	143.3	5.1	3.7	78.3	38.4	602.6	12
1970	54.8	38.5	37.4	48.8	21.6	21.9	50.6	42.6	50.5	11.7	137.4	27.4	543.2	12
1971	69.3	13.7	47.3	43.0	66.4	132.6	21.6	74.2	16.7	47.3	59.8	13.5	605.2	12
1972	50.7	50.1	56.0	38.8	28.8	15.5	19.3	9.1	30.3	14.4	45.8	53.3	412.0	12
1973	11.2	11.5	13.5	45.1	48.8	80.0	50.4	30.2	72.4	25.0	27.5	38.9	454.3	12
1974	58.3	47.3	29.4	15.3	38.0	69.8	35.1	63.9	129.5	78.1	142.9	35.2	742.7	12
Avg.	47.5	32.3	35.6	37.4	47.5	53.3	55.3	63.6	56.6	49.8	62.4	49.2		
Yrs.	21	21	21	21	21	21	21	21	21	21	21	21	21	

Yearly total of monthly averages (mm) 590.6

Average of yearly totals (mm) 590.6

Table A.5.4 Seasonal data table for Hampton *(b) Maximum hourly rainfall in mm*

Maximum Hourly Totals (mm). Station: 284152

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ov. yr.
1954	7.6	2.8	4.4	1.8	2.6	11.9	3.8	12.7	3.4	8.4	4.7	5.3	12.7
1955	13.0	3.1	3.5	0.9	5.2	6.6	2.8	3.6	8.5	4.8	4.8	2.1	13.0
1956	4.0	0.5	2.0	2.1	0.9	7.1	17.9	8.1	6.6	10.6	2.8	4.5	17.9
1957	4.0	5.4	3.6	2.6	4.9	3.9	7.0	24.0	3.5	9.0	7.1	2.8	24.0
1958	2.4	3.9	1.8	5.2	5.0	5.3	11.2	5.5	9.1	4.0	2.9	5.9	11.2
1959	4.9	0.8	2.1	5.2	5.1	5.5	5.0	5.3	0.3	4.6	6.1	5.0	6.1
1960	5.0	2.3	5.0	2.8	5.8	13.0	8.3	2.9	5.4	5.1	5.9	3.9	13.0
1961	4.2	3.5	1.4	2.6	3.4	2.9	8.4	31.1	7.6	4.1	3.3	4.4	31.1
1962	3.7	1.5	2.4	2.0	5.1	1.3	8.8	6.7	9.6	10.5	2.7	4.8	10.5
1963	2.4	0.7	2.8	4.0	3.5	3.2	8.0	4.6	4.4	3.6	11.9	2.1	11.9
1964	1.9	1.8	5.4	8.5	5.1	8.4	3.1	3.8	1.8	5.9	3.4	2.6	8.5
1965	2.6	1.9	4.1	2.9	1.9	3.7	7.4	4.1	9.9	3.7	4.1	2.6	9.9
1966	4.0	2.8	1.6	2.9	4.9	8.8	7.4	11.8	3.4	7.9	3.7	4.0	11.8
1967	4.8	5.0	2.6	3.7	7.4	11.5	16.1	7.7	5.3	5.7	4.2	4.2	16.1
1968	2.4	2.8	2.3	6.6	8.9	5.0	10.9	5.0	7.9	5.3	3.5	6.9	10.9
1969	3.5	2.6	3.2	2.1	3.9	2.6	6.7	25.2	0.9	1.3	6.9	4.5	25.2
1970	2.1	3.5	2.3	2.2	3.8	4.6	5.5	5.6	8.6	1.6	5.0	3.5	8.6
1971	4.8	1.2	3.8	4.3	4.9	5.6	4.7	14.2	4.8	3.0	8.2	2.9	14.2
1972	2.0	4.7	5.8	3.5	3.2	1.8	2.4	2.1	5.2	3.5	4.7	2.6	5.8
1973	1.5	3.4	2.1	2.6	4.2	7.8	25.9	4.8	7.4	3.6	4.7	2.8	25.9
1974	6.6	1.9	3.3	2.8	5.4	5.6	4.7	5.0	7.6	3.6	7.3	3.8	7.6
over all yrs.	13.0	5.4	5.8	8.5	8.9	13.0	25.9	31.1	9.9	10.6	11.9	6.9	31.1

Table A.5.4 continued Seasonal data table for Hampton

(c) Proportion of days without missing data

Percentage of days where all data are present. Station: 284152

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ov. yr.
1954	1.00	1.00	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1955	1.00	0.93	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99
1956	1.00	0.90	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99
1957	1.00	1.00	1.00	1.00	1.00	1.00	0.97	1.00	1.00	1.00	1.00	1.00	1.00
1958	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1959	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1960	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1961	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.94	0.99
1962	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.84	0.99
1963	0.94	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99
1964	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1965	1.00	1.00	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1966	1.00	1.00	1.00	0.93	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99
1967	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	1.00
1968	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1969	1.00	0.96	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.94	0.99
1970	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.87	0.99
1971	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	1.00	1.00	1.00
1972	0.90	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99
1973	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1974	1.00	0.96	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
over all yrs.	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	

Table A.5.4 continued   Seasonal data table for Hampton

Table A.5.5.1a ***Comparison of PEPR daily totals and microfiche trace changes (approx), in mm when rain/no rain/missing periods are inconsistent: Chandos Recreation Ground, 1957***

Date	PEPR	Microfiche	SUSPECT	Comments
05/02/57	0.0	15.5	8	Missing
07/02/57	0.0	15.5	8	Missing
20/03/57	0.0	1.3	0	Pen jump??
17/04/57	Missing	1.3	-1	??
18/04/57	Missing	0.8	-1	??
07/06/57	0.0	0.3	0	Similar
14/07/57	0.0	1.3	8	Missing
16/07/57	0.0	4.7	8	Missing
09/08/57	0.0	0.8	8	Missing
11/08/57	0.0	1.5	8	Missing
26/08/57	Missing	0.0	-1	??
23/09/57	0.0	3.3	8	Missing
24/09/57	0.0	4.3	8	Missing
16/10/57	0.0	5.0	8	Missing
17/10/57	0.0	Messy 3.3	8	Missing
28/10/57	0.0	0.5	8	Missing
29/10/57	0.0	3.8	8	Missing
31/10/57	0.0	3.3	8	Missing
02/11/57	0.0	3.0	8	Missing
04/11/57	0.0	6.0	8	Missing
15/11/57	0.5	0.0	2	Similar

Table A.5.5.1b ***Comparison of PEPR daily totals and microfiche trace changes (approx), in mm when rain/no rain/missing periods are inconsistent: Chandos Recreation Ground, 1 January to 25 April 1958***

Date	PEPR	Microfiche	SUSPECT	Comments
05/01/58	0.0	6.8	8	Missing
28/01/58	0.0	7.8	8	Missing
07/02/58	Missing	3.0	-1	??, Snow
08/02/58	0.0	1.0	8	Missing
18/02/58	0.8	Messy tr.,0.0	2	Similar
21/02/58	0.0	1.5	8	Missing
23/02/58	0.0	Messy tr., 3.8	8	Missing
24/02/58	0.0	15.3	8	Missing
25/02/58	0.0	0.0	8	Missing
04/03/58	0.4	0.0	0	Similar
06/03/58	0.3	0.0	2	Similar
05/04/58	0.0	Missing	8	Missing
07/04/58	0.0	0.0	8	Missing

Table A.5.5.2a ***Number of rain/no rain/missing day inconsistencies between PEPR and microfiche data: Chandos Recreation Ground, 1957.***

Inconsistencies	Number of occurrences
PEPR dry, microfiche rain SUSPECT=8	15
PEPR dry, microfiche>0.5mm	1
$0 < \text{PEPR} \leq 0.5$, microfiche dry	1
PEPR missing, microfiche rain > 0.5	2
PEPR missing, microfiche dry	1
PEPR dry, 0< microfiche<0.5mm	1

Table A.5.5.2b ***Number of rain/no rain/missing day inconsistencies between PEPR and microfiche data: Chandos Recreation Ground, 1 January to 25 April 1958.***

Inconsistency	Number of occurrences
PEPR dry, microfiche rain SUSPECT=8	8
PEPR dry, microfiche dry SUSPECT=8	1
PEPR missing, microfiche $\geq$0.5 mm	1
$0 < \text{PEPR} \leq 0.5$, microfiche dry	2
PEPR >0.5, Microfiche dry, but messy	1

Table A.5.5.3a Comparison of PEPR daily totals and bottle readings (mm): Chandos Recreation Ground, 26 April to 31 December 1958

Date	PEPR	Microfiche	SUSPECT
03/07/58	Missing	0.0	-1
21/07/58	0.0	2.8	0
24/09/58	Missing	0.0	-1
22/12/58	0.0	No chart	0

Table A.5.5.3b Comparison of PEPR daily totals and bottle readings (mm): Chandos Recreation Ground, 1959

Date	PEPR	Microfiche	SUSPECT
13/03/59	0.0	No marks	0
15/03/59	0.0	No marks	0
05/04/59	Missing	0.0	-1
12/04/59	0.0	5.5	0
30/05/59	0.0	No marks	0
31/05/59	0.0	No chart	0
09/06/59	0.0	1.8	0
31/08/59	0.0	No chart	0
08/11/59	Missing	0.0	-1
09/11/59	0.0	No marks	0

Table A.5.5.3c ***Comparison of PEPR daily totals and bottle readings (mm): Chandos Recreation Ground, 1 January to 25 August 1960***

Date	PEPR	Microfiche	SUSPECT
01/01/60	0.0	25.0	0
02/01/60	0.0	1.0	0
03/01/60	0.0	1.3	0
15/01/60	Missing	0.0	-1
26/02/60	0.0	6.0	0
04-06/03/60	0.0	No marks	0
14/03/60	0.0	No chart	0
17-20/03/60	0.0	No marks	0
09/04/60	0.0	1.3	0
24-29/05/60	0.0	No marks	0
29-30/07/60	Missing	0.0	-1
31/07/60	0.0	0.5	0

Table A.5.5.4a ***Chandos Recreation Ground 246738, 26/4/58-31/12/58***

	Number of days in period
PEPR missing, bottle reading=0	2
PEPR dry, bottle reading rain	1
Chart missing	1

Table A.5.5.4b ***Chandos Recreation Ground 246738, 1959***

	Number of days in period
PEPR missing, bottle reading=0	2
PEPR dry, bottle reading rain	2
PEPR dry, no marks on chart	4
PEPR dry, no chart	2

Table A.5.5.4c ***Chandos Recreation Ground 246738, 1/1/60-25/8/60***

	Number of days in period
PEPR missing, bottle reading dry	2
PEPR dry, bottle reading rain	6
PEPR dry, no marks on chart	3
PEPR dry, no chart	1

Table A.5.5.5 ***Comparison of PEPR daily totals and microfiche check gauge readings (mm) when rain/no rain/missing periods are inconsistent: Chandos Recreation Ground, 26 August to 31 December 1960***

Date	PEPR	Microfiche	SUSPECT	Comments
10/10/60	0.0	1.8	8	Missing
17/10/60	0.0	1.5	8	Missing
21/10/60	0.0	3.8	8	Missing
06/11/60	0.0	0.3	0	Similar
16/11/60	0.0	1.3	8	Missing
26/11/60	0.0	1.8	8	Missing
11/12/60	0.0	1.3	8	Missing
15/12/60	0.0	0.3	8	Missing
23/12/60	0.0	1.8	8	Missing

Table A.5.5.6 ***Number of rain/no rain/missing day inconsistencies between PEPR and microfiche data: Chandos Recreation Ground, 26 August to 31 December 1960***

Inconsistency	Number of occurrences
PEPR dry, microfiche rain, SUSPECT=8	8
PEPR dry, microfiche<0.5mm	1

Table A.5.5.7 ***Comparisons of PEPR rain values and microfiche check gauge readings, not within 0.5mm: Chandos Recreation Ground, 26 August to 31 December 1960***

Date	PEPR	Microfiche	SUSPECT
22/10/60	2.7	3.5	0
27/11/60	2.2	2.8	0

A6. Raingauges with zero monthly totals

Tables A.6.1 list raingauges which have 'dry' months. There are 35 in total.

Table A.6.1a *List of gauges which have 'dry' months*

Gauge name	Number	'Dry' months
Spring Park Farm	237611	June 1973
Riverside STW	237868	September 1972
Waltham Stow, Lloyd Park	245228	June 1976
Lowhall Farm Depot		January 1973
Green Lanes	245291	December 1963, March 1963, 1964, 1965, 1966, 1967, February, March 1968, December 1968, April 1971, December 1976
Clapton Pond	245310	January, February 1963, September-November 1964 June, July 1974
Wick Lane	245400	February 1971, June 1974
Lyle Park	246020	October 1973
Western PS	246277	January 1966, May 1970, February-May 1971
Mill Hill	246627	April 1964, February 1969, December 1970
Hampstead	246690	August 1943
Stanmore	246719	February 1960, February 1969 August 1970
Chandos Recreation Ground	246738	February 1942, March 1955, March 1956 May-December 1958, Jan-April 1959 June 1959-July 1960, September 1973
Brent Reservoir	246847	March 1948, June 1970
Ealing Castlebar	247060	June 1967
Sudbury Hill PS	247095	February, August 1956
Northolt Aerodrome	247344	July, August 1947, March 1963
Hayes, Wood End Nurseries	247449	June 1934

Table A.6.1b List of gauges with dry months contd.

Gauge name	Number	'Dry' months
Ashford Common	284058	March 1972
Maldon STW	286390	November, December 1966
Canbury Gardens	286405	January 1951, February 1952 February 1960, August, September 1963 March, April 1965, July 1969 June-August 1971
Sutton STW	287144	January 1964
Raynes Park	287203	January 1969
Putney Heath	287283	October 1965, December 1968 January-March 1969 February-April 1970, June 1970 July-September 1971
How Green Res.	287451	August 1976
Purley Oaks	287722	March 1965, September 1967
Carshalton PS	287883	February 1969, June 1971
Morden Hall	287909	February, March 1963, October 1965 November 1966, June 1967 February, March 1968, March 1969, August 1972
London Road	287946	January 1967, February 1968 April-August 1971 January, February, September 1972 March-June 1974
Furzedown Rec. Gd.	288020	August 1975
King George's Park	288065	April 1974, March 1976
Ruskin Park	288327	December 1976
Kelsey Park	288749	March 1966, March 1967 January, February 1968, March 1969
Crossness STW	290007	March, October 1965
Orpington	291241	February 1963, January 1968

A7. Updated list of available raingauge data

The original PEPR data set was supplied with a list of dates for which data are available for each raingauge site. Results from the seasonal analysis indicated that there were missing data within the limits of these dates (apart from the 'dry' periods) and that a new listing of available data should be created. This is presented as Table A.7.1. Only completely missing months have been eliminated from the list and 'dry' months are still included which, in reality, are likely to be also missing.

Table A.7.1 'Available' PEPR data

Gauge	Periods of available data
1. Bury Farm	April 1972-December 1976
2. Spring Park Farm	July 1972-December 1975
3. Riverside STW	April 1972-December 1975
4. Chigwell STW	March 1973-December 1976
5. Folkstone Road	August 1970-December 1976
6. Waltham Abbey	April 1972-December 1976
7. Muswell Hill	August 1958-November 1961 January-October 1962 March 1963-December 1966 February-October, December 1967
8. Deephams STW	April 1972-December 1976
9. Walthamstow, Lloyd Park	February-April 1974 October 1974-January 1976 June-December 1976
10. Lowhall Farm Depot	January, February 1958 April 1958-January, March 1959 June-August 1959 October 1959-January 1960 March, May-November 1960 January, February 1961 April 1961-March 1962 May, July, September-December 1962 March, April, June-November 1963 March-August, October, November 1964 January, March-July, September 1965 November 1965-September 1970 November 1970-January 1973 August 1973-December 1976

Table A.7.1 continued 'Available' PEPR data

Gauge	Periods of available data
11. Green Lanes	March-December 1963 March-November 1964 March-October 1965 March-December 1966 March-November 1967 February-December 1968 April-November 1969 April-December 1970 April 1971-December 1976
12. Clapton Pond	January-December 1960 March 1961-November 1964 January 1965-July 1974 January 1975-November 1976
13. Auckland Road	November 1971-December 1976
14. Wick Lane	January 1971-April 1973 June 1973-December 1974
15. Lyle Park	October 1973-December 1976
16. Parliament Hill	April 1974-December 1976
17. Regents Park	August 1973-July 1974
18. Western PS	October 1963-December 1967 March-December 1968 March-November 1969 March-December 1970 February 1971-December 1976
19. Kensington Memorial Gns.	April 1974-December 1976
20. Holland Park	July 1972-December 1976
21. Mill Hill	August 1960-December 1976
22. Hampstead	January 1933-December 1940 March 1941-December 1961 March-December 1962 March 1963-April 1965 June 1965-December 1975
23. Golders Hill Park	January-December 1976
24. Stanmore	January 1942-January 1945 March 1945-February 1947 June 1947-December 1971
25. Canons Park	October 1973-December 1976
26. Chandos Rec. Ground	January 1942-May 1945 September 1945-January 1956 March 1956-September 1973

Table A.7.1 continued 'Available' PEPR data

Gauge	Periods of available data
27. Brent Reservoir	March 1948 January 1949-December 1950 July 1953-December 1976
28. Harrow Weald Cem.	January 1972-December 1976
29. Wembley	January 1964-December 1965 February 1966-September 1969
30. Gladstone Park	January 1969-January 1972 April 1972-December 1975
31. Willesdon Works	April 1972-December 1976
32. Stonebridge Park	January 1966-September 1970 September 1971-November 1975
33. Ealing Castlebar	February 1962-December 1965 March 1966-March 1970 July 1970-January 1974 September 1974-September 1976
34. Brentside School	September 1961-December 1962 March 1963-August 1971
35. Sudbury Hill PS	November 1953-October 1956
36. Pinner Cemetery	January 1957-April 1961
37. Northolt Aerodrome	September 1946-December 1973
38. Newton Park Depot	February 1975-December 1976
39. Hayes, Wood End Nurseries	October 1928-May 1930 August 1930-March 1937 May 1937-August 1938 October, November 1938 January 1939-January 1941 March 1941-May 1944 June 1961-September 1974
40. Perry Oaks	April 1972-December 1976
41. Hatton Nurseries	January 1973-December 1976
42. Twickenham STW	January 1941-November 1942 January 1943-April 1945
43. Mogden STW	January 1969-December 1976

Table A.7.1 continued *'Available' PEPR data*

Gauge	Periods of available data
44. Ruislip	February 1957-January 1963 March 1968-December 1976
45. Uxbridge, Honeycroft NRS	October 1974-December 1976
46. Ashford Common	March 1972-December 1976
47. Hampton	January 1954-December 1974
48. Epsom Water Works	April 1971-September 1974
49. Maldon STW	August 1957-December 1966
50. Hogsmill STW	July 1957-January 1959 March 1959-December 1976
51. Canbury Gardens	February 1948-August 1960 October 1960-December 1961 January 1963-December 1976
52. Kew Observatory	July 1944-December 1974
53. Kew STW	August 1966-December 1976
54. Sutton STW	October 1936-December 1938 January 1940-December 1945 January 1947-December 1974
55. Raynes Park PS	November 1960-December 1961 October, December 1964- December 1976
56. Putney Heath	June 1964-June 1970 August 1970-December 1976
57. Banstead	February 1967-March 1971 November 1971-December 1974
58. How Green Reservoir	May 1972-December 1976
59. Alderstead Heath	October 1962-December 1968
60. Purley Oaks	March 1965-November 1972
61. Beddington Park	October-December 1962 April 1963-December 1964
62. Beddington STW	January 1972-December 1976

Table A.7.1 continued *'Available' PEPR data*

Gauge	Periods of available data
63. Carshalton PS	April 1965-September 1970 November 1970-June 1971
64. Morden Hall	January 1960-May 1965 July 1965-September 1966 November 1966-January 1969 March 1969-December 1976
65. London Road	January 1965-February 1972 September 1972-December 1976
66. Gap Road Cemetery	January 1972-December 1976
67. Furzedown Rec. Grd.	April 1974-December 1976
68. King George's Park	April 1974-December 1976
69. Battersea Park	April 1974-December 1976
70. Ruskin Park	April 1974-December 1976
71. Telegraph Hill	April-December 1974 January-December 1976
72. Earl PS	January 1972-December 1976
73. Kelsey Park	April-November 1965 March, May-December 1966 March, May-November 1967 January, February, April-August 1968 October 1968-March 1969 July 1970-December 1974
74. Crossness STW	March, October 1965-September 1970 November 1970-December 1974
75. Westerham Hill PS	April 1972-July 1974 November 1974-December 1976
76. Keston	July 1972-December 1976
77. Orpington	January 1963-November 1971

A8. Conclusions

Despite improvements in understanding the PEPR data format other uncertainties have become apparent. These have mainly concerned the presence of occasional 'dry' months in PEPR seasonal totals, when the microfiche data are known to be missing and the month often known to have had some rain. At least from the gauges analysed it would appear that there is generally good consistency between PEPR and microfiche data for rain/no rain/missing days apart from periods when there are large blocks of microfiche data missing. It appears that it is during these blocks of missing microfiche data that most of the problems occur, e.g. for one of the 'dry' months examined the PEPR dataset gave all but one day of that month correctly as missing, but for some unknown reason gave one day in that month being present and dry - hence the whole month being given as dry. For another gauge, during a missing microfiche period the PEPR record indicated all dry periods correctly and gave all wet periods as missing, which meant that the monthly total was given as zero. There seems to be little consistency and based on this restricted analysis it is unwise to make any generalisations about how the PEPR data should be used (if at all) during these periods.

Despite these ambiguities, analyses using the PEPR record were continued. with the understanding that the validity of the results (especially those concerning return periods) must be open to question, without any quality control being carried out.

On a more positive note, a lot of analyses depend on selecting events where the rainfall is always greater than zero, with zero rainfall at each end, and without any missing data in between. Given that periods most associated with missing microfiche data seem to be those which cause most uncertainties and that much of the data examined outside these periods were fairly good, it seems that analyses based on periods when rain occurs and where microfiche data are obviously present, must be more reliable. However, errors may occur in the rare event of there being a zero at the beginning of a storm period which should be missing because it occurs at the end of a missing block. For inter-event periods to be identified there needs to be an event either side of them, with no missing data in between. Unless a missing microfiche period occurs where all of the missing data are incorrectly given as dry the chances of an inter-event period being chosen incorrectly are small; given that is, an assumed valid dataset outside these missing periods. However, uncertainties concerning the data generally and the possibility that these inter-event periods may be chosen when the data are really missing should always be borne in mind.

The Bilham analysis does make a count of all days being given as present. Therefore, because the count may be too high due to the presence of these 'dry' days, only years which do not contain these 'dry' months are used when carrying out the Bilham analysis.

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