# Flood Studies Report
in five volumes

# Volume II

# Meteorological Studies

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# Preface to the third binding

The period 1981 to 1993 has seen many developments in flood hydrology. Although the basic philosophy of flood estimation using FSR techniques remains unchanged, there have been notable enhancements which are directly relevant to the use of this report.

A further nine Flood Studies Supplementary Reports (FSSR Nos. 10 to 18) have been issued to subscribers. The recommendations in these reports supersede some given in the original report. Supplementary Report No. 5 extended application of the report more fully to urbanized catchments, but has itself been partly superseded by FSSR 16. These and other revisions made it necessary to withdraw Institute of Hydrology Report No. 49, *Methods of flood estimation: a guide to the Flood Studies Report.* Help with the intricate revisions presented to users has been provided by the recent publication of Institute of Hydrology Report No. 114, *Reservoir flood estimation: another look,* and, most importantly, version 2 of the Micro-FSR computer package.

The opportunity has been taken to bind the Flood Studies Supplementary Report series into the main Flood Studies Report, and the option of purchasing FSR maps in flat (rather than folded) form has been withdrawn. Subscribers have been informed that the FSSR series is now closed. The notification has been accompanied by a reprint of the 1983 list "Some papers of interest to Flood Studies Report users" and a new bibliography "Additional papers relating to the Flood Studies Report, 1983 to 1992". In this third binding, these lists appear at the end of the second volume, after the FSSRs.

The Ministry of Agriculture, Fisheries and Food (MAFF) support substantial research programmes related to river and coastal flood defence. A review of their flood estimation research strategy is expected to recommend targeting some of this research towards producing successor publications to the FSR. Those publications dealing with statistical flood frequency analysis are expected to present substantially new material, while those dealing with the rainfall-runoff method and the incorporation of local information are expected to consolidate the presentation of existing guidance.

Pending these new publications, specific recommendations arising from current research (notably on small catchment response times) will be published in the Institute of Hydrology's main report series.

A separate objective is the development of advanced methods of flood estimation based on continuous simulation of catchment response. Such methods will use models that more fully reflect physical processes and which are better able to exploit the detailed topographical and physiographic data that are becoming available. These will take time to succeed and meanwhile it is gratifying that methods from the Flood Studies Report stable continue in widespread use some 20 years after the original study.

Institute of Hydrology

March 1993

# Preface to the second binding

In binding further copies of the Flood Studies Report, the opportunity has been taken to include the corrigenda as separate lists in the front of each volume. The corrigenda are those which were notified to original buyers in December 1977 plus the more significant corrections which have been noted recently. The correct version of Figure 3.6 in Volume II is now bound into place. Also, an error on Map II.3.5 (S) in Volume V has been corrected on the map itself.

The errors which remain in the text of the report and which are significant in application of the methods are those on p. 344 and p. 473 of Vol. I and p. 16 of Vol II. Otherwise, the corrigenda listings are of errors or misprints which relate to the mathematical development of the methods or the values of catchment characteristics.

Since original publication in 1975, a number of brief supplementary reports have been produced and made available in a separate ring file. With this second binding, the ring file is being included with the five main volumes of the Report and all purchasers will receive further supplementary reports as and when they are produced.

Supplementary Report No. 7 was originally accompanied by a revised 'SOIL' map (Fig. I.4.18) but this is now included in Vol. V in place of the original map.

Also included with the five volumes and the ring file is a copy of the slim guide to the use of the Report's methods. Further copies of this guide may be obtained free of charge from the Institute of Hydrology.

The Report has been the subject of two conferences organised by the Institution of Civil Engineers and a seminar at the University of Birmingham. The London conference in May 1975 was designed to publicise the existence of the Report and most of the papers were written by Report authors giving further details of the procedures or illustrating different aspects of its potential areas of application. The Birmingham seminar of March 1977 was an opportunity for users and critics of the Report to discuss problems in application; a summary of the main points is given in Supplementary Report No. 3. The Manchester Conference of July 1980, entitled 'Flood Studies Report—Five Years on', included a number of papers giving examples of engineers' experience in applying the methods as well as some by researchers with details of recent advances.

The proceedings of the two ICE Conferences can be obtained from the Institution's publishing company, Thomas Telford Ltd. (PO Box 101, Telford House, 26-34 Old Street, London EC1P 1JH, UK).

Institute of Hydrology
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January 1981

# Preface

The investigations of methods of flood estimation for engineering design purposes, which are described in this report, were carried out at the Institute of Hydrology, the Meteorological Office and the Hydraulics Research Station, with the co-operation of the Irish Office of Public Works and Meteorological Service, the Soil Surveys and other organisations.

The Flood Studies Report consists of five volumes. Volume I contains the hydrological studies, Volume II the meteorological studies, Volume III the flood routing studies, Volume IV the hydrological data, and Volume V the maps.

Cross-references to sections, equations and figures are by chapter numbers, preceded by a volume number if necessary. Thus, Section I.3.5.2 is in Chapter 3 of Volume I. Equations are numbered consecutively within chapters, except in Chapters 1 and 2 of Volume I where it was necessary to number them within subsections. Figures are numbered consecutively within chapters; certain figures illustrating Volumes I and II are contained in Volume V.

The chapter titles illustrate the scope of the report.

**Volume I—Hydrological studies**

A Introduction
1 Statistics for flood hydrology
2 Statistical flood frequency analysis
3 Methods of extension of short records
4 Estimation of flood peaks from catchment characteristics
5 Estimation of flood volumes over different durations
6 Synthesis of the design flood hydrograph
7 Supplementary studies: snowmelt runoff, conceptual catchment model and flood routing
8 Future research and investigation needs

**Volume II—Meteorological studies**

1 A guide to procedures and contents of Volume II
2 Regional analysis of point rainfall extremes
3 Estimation and mapping of M5 (5 year) values for different durations
4 Estimated maximum falls of rain
5 Areal rainfall
6 Storm profiles
7 Snow cover and snowmelt
8 Examples of rainfall estimates for the Tyne and Wansbeck catchments
9 Some historic heavy rainfall events

**Volume III—Flood routing studies**

1 Choice of a flood routing method
2 Theory of flood routing
3 Comparison of flood routing methods
4 Strategy for flood routing
5 Appendices

**Volume IV—Hydrological data**

1 Collection of records
2 Data used in statistical analysis
3 Data used in unit hydrograph analysis
4 Historical flood records

5 Master list of gauging stations, catchment characteristics and flood statistics
6 Basic flood records

**Volume V—Maps**

The following maps illustrating Volumes I and II are contained in Volume V. (S indicates the southern part of Great Britain, N the northern part, and I indicates Ireland.)

| | | |
|---|---|---|
| I.4.18 | (S, N and I) | Winter rain acceptance potential |
| I.4.19 | | Estimated mean soil moisture deficit |
| I.4.20 | | River gauging stations used in analysis |
| I.4.21 | | Mean annual flood (BESMAF) |
| I.4.22 | | Coefficient of variation of annual flood |
| I.4.23 | | Residuals from BESMAF prediction equations |

| | | |
|---|---|---|
| II.3.1 | (S, N, I and NI) | Average annual rainfall |
| II.3.2 | (S, N and I) | 2 day M5 rainfall |
| II.3.3 | (S, N and I) | 2 day M5 rainfall as % of AAR |
| II.3.4 | | 25 day M5 rainfall |
| II.3.5 | (S, N and I) | 1 hour M5 expressed as % of 2 day M5 |
| II.4.1 | | Estimated maximum 2 hour rainfall |
| II.4.2 | | Estimated maximum 24 hour rainfall |

This volume, which forms Volume II of the Flood Studies Report, deals with the meteorological aspects of floods. The work was carried out in the Meteorological Office. A. F. Jenkinson, ISO, MA, was the team leader; he was responsible for the basic philosophy and wrote most of the report. He was assisted by the following personnel: M. C. Jackson MSC, who wrote Chapters 7 and 9; D. M. Pusey who was responsible for the computer programs; K. E. Woodley mapped the average annual rainfall (1941–70) and was responsible for drawing the other diagrams; Betty C. Kingston, Hilary A. V. Smith, Thelma P. Powell and P. R. Larke carried out the general data handling. After receiving comments on the first draft from members of the Steering Committee and others, J. F. Keers, BSC, undertook general editing and wrote most of Chapter 1. The Director, Meteorological Service of the Republic of Ireland, supplied rainfall data for the Republic of Ireland and was responsible for the relevant analysis of Figure 3.1 (I) and Figure 3.2 (I). The permission of the Director General, Ordnance Survey, to reproduce map information is acknowledged. Crown copyright is reserved.

The members of the Flood Studies Steering Committee were the late Mr M. Nixon (Chairman) who was succeeded as Chairman by Mr E. J. K. Chapman (ICE) in 1974, Mr G. Cole (MAFF), Mr V. K. Collinge (WRB), Mr D. Fiddes (TRRL), Mr J. Harding (MO) succeeded by Mr R. Murray and Mr J. F. Keers, Mr A. F. Jenkinson (MO), Mr M. A. Lynn (OPW, Dublin), Mr M. Mansell-Moullin, Dr J. S. G. McCulloch (Director, IH), Mr J. C. Munro (SDD), Dr J. V. Sutcliffe (IH), Mr J. I. Taylor (ARA), Mr S. F. White (DE) and Professor P. O. Wolf.

## Corrigenda to Volume II

p.16, Table 2.7 — For M5 = 200, growth factor for M20 should read 1.19, not 1.30

p.16, Table 2.8 — The correct version of Table 2.8 is attached

Table 2.8 Generalised *c*, M5 relation for rainfall growth curves, Scotland and Northern Ireland.

| M5 (mm) | *c* | M5 (mm) | *c* |
|---|---|---|---|
| 0.5 | 0.171 | 40 | 0.185 |
| 2 | 0.180 | 50 | 0.175 |
| 5 | 0.200 | 75 | 0.155 |
| 10 | 0.218 | 100 | 0.139 |
| 15 | 0.220 | 150 | 0.119 |
| 20 | 0.212 | 200 | 0.103 |
| 25 | 0.205 | 500 | 0.077 |
| 30 | 0.198 | 1000 | 0.066 |

p.33, 1.16 — Add 'The maximum rainfall for a month or season may be estimated from the annual maximum rainfall. The ratio of the extreme in a month or season to that in the year should be taken as the corresponding 100 year ratio from Section 2.4'.

p.80, 1.41–42 — For JENKINSON, A.F. (1974) substitute JENKINSON, A.F. (1975) Extreme value analysis in meteorology. 4th Conference on probability and statistics in atmospheric sciences. American Meteorological Society, November 1975, 83-89.

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# Notation

| | |
|---|---|
| $A$ | area ($km^2$) |
| AAR | average annual rainfall |
| ARF | areal reduction factor (factor for converting point rainfall into areal rainfall) |
| $B$ | a coefficient which increases with average annual rainfall |
| $c$ | an index defined by $\mathrm{M}T/\mathrm{M5} \propto T^c$, where $\mathrm{M}T$, M5 and $T$ are as defined below |
| $D$ | duration (hours) |
| $F(x)$ | the probability that an annual maximum is less than $x$ (in the range 0–1) |
| H1 | the highest value of a series of annual maxima (similarly H2, H3 and H4 are the second, third and fourth highest values) |
| $I$ | rainfall intensity (mm/hour) |
| $I_0$ | the instantaneous rainfall intensity (for very short durations) |
| $M$ | snowmelt (mm/day) |
| M2, M5, ..., M$T$ | the value with return period 2, 5, ..., $T$ years, derived from the series of annual maxima |
| M$T$/M5 | ratio of the once in $T$ years rainfall to the once in 5 years rainfall, known as the growth factor |
| $N$ | the number of years of record (or the number of annual maxima) |
| $n$ | a coefficient known as the continentality factor |
| $\rho$ | density |
| QM1 | mean of the first quartile of a series of annual maxima (similarly QM2, QM3 and QM4 are the second, third and fourth quartile means) |
| $r$ | the ratio of 60 minute M5/2 day M5 |
| $R$ | rainfall |
| $RC$ | calendar month rainfall |
| $T$ | return period in years |
| $T$M | the value which on average recurs $T$ times a year, in a partial duration series |
| $x$ | an extreme value of rainfall |
| $y$ | the reduced variate, defined by $F(x) = \exp(-\exp(-y))$. |

# 1 A guide to procedures and contents of Volume II

## 1.1 Introduction

Engineers concerned with river management and drainage works are constantly faced with the problem of suitable design criteria. Design work may involve determining the optimum storage capacity of reservoirs, flow capacities of channels and storm sewer systems, the optimum size and strength of all kinds of barrages, spillways, and so on. Economic considerations are important, and the choice of a suitable return period for a given event has a major bearing on the cost of projects.

Good quality flood data for a large number of years are not generally available; also the network of data is unsatisfactory. However, very extensive rainfall records are available in the British Isles, and these data are exploited in this report; statistical and physical studies of rainfall depth–duration–return period are made for point and areal rainfall everywhere in the British Isles. These rainfall statistics can be used by hydrologists and engineers as input to various models in order to compute the probability and the characteristics of flooding on different time and space scales.

In the United Kingdom designs are commonly based upon rainfall events with a frequency of between once in 2 years and once in 100 years: hereafter a special notation will be used to denote the return period, e.g. 2M = twice in 1 year, M2 = once in 2 years, M100 = once in 100 years, etc. In general, urban storm sewers are designed for the shorter return period events, less than M10, whilst river engineering problems are often concerned with the events of longer return period, up to or more than M100. Some structures must be designed to a very high degree of safety and then an estimate of the M1000 event, or even the estimated maximum precipitation, may be required.

## 1.2 A brief history of the development of rainfall depth–duration–return period relationships

Before the mid-1930s the analysis of rainfall records led to very crude results, mainly because rainfall records were inadequate. However, there was a great demand for rainfall depth–duration–return period relationships and in 1930 a committee on rainfall and runoff was set up under the Ministry of Health. Their report included analysis of 7 years of rainfall charts from 14 'widely distributed' stations and the Ministry of Health curve, produced for rainfall durations from 5 to 100 minutes, was widely used for a long time (Fawcett, 1930). One serious weakness, however, was that the frequency or probability of occurrence of the rainfall events represented by the curve was not precisely specified. Another weakness was the wide scatter of stations, which meant that results were an approximate average for the whole country.

Rainfall analysis of a new kind was produced by Bilham (1935). He used data for 10 years from 18 stations and for the first time full use was made of the standardised tabulations of rainfall intensity–duration–frequency which had been consistently maintained by Meteorological Office stations for a number of years. A soundly based frequency or probability analysis had become possible. However, because the data available were still very limited the results were an average for the country and the rare event could only be estimated very roughly. Also, the results were only applicable to rainfall of durations between 5 minutes and 120 minutes although extrapolations were made to durations of up to 24 hours.

A number of investigators have re-analysed rainfall data of the same type as used by Bilham but usually covering a longer period of years. Several different curves or formulae have been devised to fit the actual data points but serious divergencies become apparent in extrapolating to events of a rarity up to or beyond the length of the data period, mainly because the curve-fitting and extrapolation techniques are not always based on a statistical theory of extreme values. In such cases the use of extreme value theory, as developed by Gumbel (1959) and Jenkinson (1969) and others, considerably reduces sampling errors.

Design practices for stormwater drainage in urban areas came under review in the early 1950s when a comprehensive research programme was established by the Road Research Laboratory, in collaboration with the Meteorological Office and the Hydraulics Research Station. The work continued well into the 1960s and culminated in Road Note No. 35 (McNaughton, Wells & Manzoni, 1963). With the introduction of computer methods in the early 1960s a digital simulation model for urban rainfall runoff was introduced, and is widely used by engineers. The model incorporates a rainfall intensity profile.

### 1.3 The rainfall data

The extensive rainfall data consist mainly of daily values measured from 0900 to 0900 GMT. Daily totals at more than 600 stations with average length of record 60 years and a further 6000 stations for the 10 year period 1961–70 are employed in this report. These data have been carefully analysed and checked for quality, by computer and by hand, and finally written to magnetic tape.

There are only a few hundred stations equipped to measure short duration rainfall and few of these have records for more than 25 years. The common type of record from these stations is the daily chart which is produced by an autographic raingauge. The extraction of rainfall amounts for various durations from these charts is a time consuming task. Tabulations of hourly rainfalls and frequency tabulations for some other durations, similar to those used by Bilham (see 1.2), are available in the Meteorological Office archives for some 140 stations. Altogether records from approximately 200 autographic raingauge stations, 101 of which had 20 or more years of record, were analysed for this report. Short duration data from the limited period experiments at Cardington and Winchcombe and the Jardi rate of rainfall data for several places were also used. Rainfall for a wide range of durations can be obtained from the above data.

The problem of a major weather system giving significant amounts of rain such that the 0900 hours rainfall observation separates the rain into two less significant daily falls, is successfully overcome by analysing 2 day rainfalls. The 60 minute and 2 day rainfalls are basic statistics in this report and rainfall of intermediate durations is related to them.

Monthly rainfall data exist for a further 1000 stations which, together with the monthly totals derived for the daily stations, give nearly 7000 monthly stations. In this report the results of analysing calendar month data are expressed in terms of any period of 25 days; the justification for this procedure is that the M5 value for a calendar month was found to be approximately equivalent to the M5 value for 25 days.

## 1.4 The statistical analysis of the data

For a single daily rainfall station with, say, 60 years of record, an elementary statistical analysis (counting the cases) can be relied upon to give a reasonably accurate value of the 2 day M5 or even the 2 day M10 for that geographical location. However, for the rarer event the sample is unlikely to be representative. Due to the random nature of extreme rainfall, the 60 years may contain none, one, two or even more 2 day M60 events. A statistical theory of extremes such as that devised by Jenkinson (1969) is used to overcome this difficulty to a large extent, though it does not enable extrapolations to events of a rarity much beyond the length of the data period for a single station.

The extreme rainfall events for a particular duration are analysed by considering only the annual maximum values. If a great number of years of record are available, 5 year maximum values are perhaps even more appropriate. It is shown in Chapter 2 of this volume that the very simple method of dividing the ordered set of annual maxima into four quartiles and identifying the quartile means as follows, gives results in good agreement with extreme value theory. The first quartile mean is identified with 2M, the mean of the middle two quartiles with M2, the mean of the upper two quartiles with M5, the fourth quartile mean with M10. The four highest values of the ordered data set of annual maxima are used to estimate, with less confidence, the rarer events up to M*n*, where *n* is the number of years of record.

The following is an outline of the method of deriving the M100 or even rarer event from a large number of rainfall stations each with 60 years of record. Consider, for example, the rainfall of duration 2 days. First the 2 day M5 value for each station is determined by computing the mean of the upper two quartiles of the ordered data set of 2 day annual maxima. Then the stations are grouped into classes depending on the value of the 2 day M5. One such class is, for example, for stations with 2 day M5 between 40 and 50 mm. There are 175 stations in this class out of a total of 600 long period stations, and the 2 day rainfalls for all these stations are considered as a single set consisting of 10 500 annual maxima. The application of the quartile analysis scheme to the set of 10 500 annual maxima, in the same way as to values for a single station, enables reliable estimates of 2 day events as rare as M1000 and less reliable estimates of M10 000 to be made. The assumptions which are inherent in such a scheme of combining station records are

*1* the annual maximum events are independent, and

*2* the 60 year, 175 station set of 2 day annual maxima will contain a selection of falls sufficiently varied to represent a very long period.

Neither of these assumptions can be guaranteed to be satisfied for any combination of stations, but for the extreme rainfall events *1* is reasonably well satisfied for the station network considered, only 600 stations covering the whole of the British Isles. On the other hand, the station network is dense enough to assume that some extreme point rainfalls, if not the maximum possible rainfall, will have been recorded at some of the stations, in each class of M5, during the 60 year period. Also, it is likely that most, if not all, of the possible combinations of weather types have occurred in the last 60 years.

### 1.5 A simple introduction to the 'growth factor'

Considering the 2 day rainfall at stations with M5 between 40 and 50 mm and plotting the logarithm of the return period against the logarithm of the rainfall amount, a smooth curve can be drawn through the points as shown in Figure 2.3 (curve c) of Chapter 2. This curve is called the growth curve of the 2 day rainfall for M5 between 40 and 50 mm. Similar curves can be drawn for M5 rainfall of other durations and other ranges of M5. Thus, a whole family of curves is produced, all having a similar shape. This leads to the idea that once the M5 value is determined the value of M*T*, where *T* may have any value, can also be determined. The ratio of M*T* to M5 for rainfall of any duration is related to M5 and this relationship is given in graphical form in Figure 2.4. The ratio M*T*/M5 is called the growth factor. The growth factor varies slightly with geographical location and this is taken into account by considering the country as two regions, *i* England and Wales and *ii* Scotland and Northern Ireland. Growth factors are given in Tables 2.7 and 2.9.

### 1.6 Mapping the geographical distribution of M5 for 60 minute, 2 day and 25 day rainfall

It was seen in 1.5 above, that once the M5 value for a given rainfall duration is determined, the values for other return periods can be derived from a knowledge of the growth factor. Therefore, the key process in determining the return period of any rainfall event at any location is the production of maps giving the detailed geographical distribution of M5 values. The mapping procedure is fully described in Chapter 3. The following is a brief outline of the main ideas.

Detailed maps of M5 were produced for 2 day, 2 day as a ratio of AAR (annual average rainfall), 25 day as a ratio of AAR, and 60 minutes as a ratio of 2 day rainfall, as shown in Figures 3.2, 3.3, 3.4 and 3.5 respectively: the first two and last figures are in three parts, namely south Britain, north Britain and Ireland, and all are to be found in Volume V. These maps, excluding the last, were drawn subjectively using the plotted values from 6000 stations for Figures 3.2 and 3.3, and from 7000 stations for Figure 3.4. The chief aim of the analyst was to relate the pattern closely to the field of topography in regions where the data were sparse.

The corresponding problem of mapping 60 minute M5 rainfall could not be dealt with by analysing the rainfall data alone. There were not enough station values and many that were available were for less than 20 years of record. Therefore, an indirect method of analysis was employed, which relied upon finding relationships between the short duration rainfall data that were judged reliable, and such independent parameters as the average number of days with thunder heard, the M5 precipitable water and even the 2 day M5 rainfall.

Empirical relationships relating 60 minute M5 with the other variables were used to compute 60 minute M5 values at each gridpoint of a $10 \times 10$ km grid covering the British Isles. These values, together with the original M5 values, were used to derive the map of 60 minute M5, shown in simple form in Figure 3.6, and in detail as the ratio of 2 day M5 in Figure 3.5. Because an indirect method was used some individual station values are not compatible with the final analysis.

## 1.7 Relating the 60 minute M5, 2 day M5 and 25 day M5 with M5 rainfall for other durations

Rainfall data for durations other than 60 minutes, 2 days and 25 days were analysed and the M5 values for them were related to the M5 values for these three basic durations. The results are presented in Chapter 3 in the two main Tables 3.2 and 3.10.

It is of course intended that M5 values for 60 minutes, 2 days and 25 days, and average annual rainfall, for any location, should be obtained from the detailed maps provided. It is also intended that M5 values for particular durations between 48 and 72 hours, between 72 and 96 hours, and between 96 hours and 25 days should be obtained by linear interpolation on a logarithmic graph of rainfall versus duration.

The M5 rainfall for any duration of less than 48 hours is obtained from Table 3.10. The required M5 value is obtained as a percentage of the 2 day M5 and is thus easily calculated in millimetres of rainfall once the 2 day M5 is extracted from the detailed map (Figure 3.2).

## 1.8 Outline of the scheme for obtaining point rainfall for any chosen location, duration and return period

The basic scheme for obtaining the point rainfall for any duration and return period is first to determine the appropriate M5 value, as outlined in 1.7 above, and then to use Table 2.7 (for England and Wales) and Table 2.9 (for Scotland and Northern Ireland) to determine the rainfall for any other return period. This scheme is so important for many of the questions that need to be answered that it is useful to list the detailed steps as follows.

*a* The required location is identified by its National Grid Reference (NGR).

*b* The NGR is used to determine accurately the required location on maps of the 2 day M5 (Figure 3.2) and the ratio $r$ = 60 minute M5/2 day M5 (Figure 3.5).

The values of 2 day M5 and $r$ are then extracted.

*c* Using Table 3.10, and interpolating for the value of $r$, the M5 value for the appropriate duration is obtained as a percentage of the 2 day M5 and is thus easily calculated. If the duration is greater than 48 hours, however, the appropriate M5 value is determined as outlined in Section 1.7 above.

*d* Using Table 2.7, and interpolating for the value of M5, the rainfall amount, expressed as a ratio of the M5 rainfall, is obtained for any return period.

## 1.9 The estimation of maximum precipitation

In Chapter 4 the geographical distribution of estimated maximum 2 hour and 24 hour precipitation is determined using a storm efficiency factor and an analysis of maximum dew point (Figures 3.1 and 3.2). The rainfall maxima for durations less than 2 hours are related to the 2 hour maxima in Table 4.1. The estimated maxima for durations between 24 hours and 25 days are related to the 24 hour maxima in Table 4.3. The estimated maximum for durations between 2 and 24 hours is determined by linear interpolation on a diagram of rainfall versus the logarithm of the duration.

Maxima are also estimated from the statistical analysis of point rainfall relying on an envelope of all the data on the diagram of growth curves (Figure 2.3). The results are in broad agreement with those obtained using the storm efficiency factor.

### 1.10 The areal reduction factor

Depth–duration relationships for areas of different sizes are derived in Chapter 5. Relations are found between areal rainfall over fixed catchment areas of many different sizes, and the point rainfall with the same duration and return period. These relations specify an areal reduction factor which when multiplied by point rainfall gives the corresponding areal rainfall This enables many of the results for point rainfall derived in earlier chapters to be applied to areal rainfall. The areal reduction factor increases with increasing rainfall duration and decreases with size of area, but the variation with geographical location is apparently not very significant.

### 1.11 The storm intensity profile with time

Many of the models used in hydrological research and design investigations require input which varies with time, for example the TRRL unit hydrograph method of designing surface water sewer systems. The time variation of point and areal rainfall can be described by a storm profile. In order to describe fully the rainfall over an area, however, a storm profile is required for a number of points over the area. In this way the response of land drainage to rainfall can be determined for any combination of storm intensity and storm movement. The results of a detailed analysis of many large storms of different durations are discussed in Chapter 6. In order to take account of the great variety of storm profiles certain simplifications are required. The present study obtains useful results by regarding the storm as being centred on the shortest period giving 50% of the rainfall.

The results are presented so that the reader can readily extract the storm profile which might be exceeded in peak intensity by one storm in ten, for example. Summer and winter storm profiles are considered separately, and differences due to regional and rainfall type are incorporated in the seasonal difference. Little difference is found between profiles of point rainfall and profiles of areal rainfall for different sized areas and the corresponding duration of practical interest. However, the peaks of areal profiles are a little flatter than the corresponding peaks of point profiles.

The variation of peak intensity with duration and return period is not significant compared with the variation of peak intensity between individual storms. However, the variation with duration, for example, could be significant in extreme cases and it is perhaps worth mentioning that for longer duration rainfall events, i.e. 24 hours or longer, the profiles for mountainous areas will not be as peaky as those depicted in Figures 6.1 and 6.2.

### 1.12 Snowmelt

Many problems concerning rainfall and the associated flood are complicated by other contributory factors, such as snowmelt. It is rarely the sole cause of a serious flood in the United Kingdom, although it is known to be significant in certain circumstances, for example when warm air associated with heavy rain spreads over a deep snow covered surface.

Snowmelt can be significant in the years when several snowfalls over a period of weeks or months result in a deep layer of snow of large water equivalent. A recent such occasion in the United Kingdom was in 1962–63, two before being in 1946–47 and 1939–40. In 1947 there were large scale catastrophic floods, especially in the Fens of East Anglia, in some other parts of south and south east England, and in several parts of Yorkshire. Snow accumulation in 1962–63 was appreciably less and in general the thaw came slowly over a rather prolonged period with little flooding. Thus, there are few opportunities to improve snowmelt forecasting techniques.

Chapter 7 outlines a scheme for determining a rare snowmelt, i.e. return period 100 years or more. The main variables examined are the temperature (the daily maximum and the 3 hour accumulated temperatures), snow depth and the density of snow. The frequency distribution of annual maximum temperatures (Table 7.3) with snow lying and an analysis of snow densities are presented. A map of the median annual maximum snow depth (Figure 7.2) and a summary of the depth frequency relation (Table 7.1), are provided. Volume I, Chapter 7 describes a model for computing runoff from snowmelt.

## 1.13 Worked examples to illustrate the methods of rainfall estimation

The first example in Chapter 8 is for a catchment area of approximately 3000 km$^2$ and it answers the question, 'what is the depth of rainfall at a point for different durations and return periods in each of three distinct rainfall regions of the catchment, and what is the catchment rainfall for different durations and return periods?' The latter is deduced from a direct application of the areal reduction factor for the particular durations and an area of 3000 km$^2$. It is **recommended** that the results derived from analysing a local rainfall record should not be used to adjust the results obtained using this report.

The reader should be able to use Chapter 8 as a practical work guide, referring to other chapters only for specified tables and diagrams. The steps in the computational procedure are set out in order at the beginning of the chapter. After working through the calculations for a selected catchment, following the methods used in the examples of Chapter 8, and gradually assimilating the essentials if not the details of the other chapters, he should become quite fluent in the use of the methods.

Having derived the rainfall depth–duration–area–return period relationship and the storm profile from this volume, the flood discharge of any desired return period is computed by the method described in Section I.6.8.

## 1.14 Rainfall cycles

None of the methods described in this report takes account of climatic change. From studies of the limited amounts of data available for the eighteenth century and the more plentiful data for the nineteenth century there seems no reason to believe that the intensity–duration–frequency characteristics of rainfall over the British Isles were markedly different from those of the past 100 years from which the data analysed in this report have been drawn. There would thus appear to be little justification for making adjustments to rainfall estimates for return periods of 50 years or more.

Irregular or quasiregular fluctuations of periods less than 50 years might be of some practical significance if the range of the rainfall fluctuations were sufficiently large. But only the short period (12 years or less) quasiregular fluctuations appear to be large enough to be of much practical importance (see Section 3.5). These fluctuations are probably greatest for short duration rainfall.

### 1.15 Major rainfall events of the past

No meteorological report on floods in the United Kingdom would be complete without reference to major rainfall events. Chapter 9 contains facts and figures about 10 extreme rainfall events in the United Kingdom.

# 2 Regional analysis of point rainfall extremes

## 2.1 Summary

Sets of annual point rainfall maxima $x$ for a given duration are grouped together in suitable classes according to magnitude of M5, the 5 year return period value. For each class, the median values of $x$ against return period $T$ give a 'growth curve' which stabilises each individual set of data in the class; the maximum values, H1, for each set of data in the class, are standardised and used to extend the growth curve to higher return periods (Jenkinson, 1969).

For a given region, the set of growth curves for a given duration form a family of similar curves with the sets for other durations. Thus, a complete set of growth curves for the region can be compiled, which can be used as standard curves for given M5 values. Hence, the ratios M$T$/M5, which may be termed 'growth factors', can be compiled for given values of M5.

The regional analysis of growth factors for the British Isles is presented for only two regions, namely England–Wales and Scotland–Northern Ireland. The growth factors M$T$/M5 are tabulated against values of M5 for England and Wales in Table 2.7; and for Scotland and Northern Ireland in Table 2.9.

## 2.2 Graphical analysis of a set of annual maxima

If we arrange a series of $N$ annual maxima in ascending order $X_1, X_2 \ldots X_m \ldots X_N$, and $F(X_m)$ is the cumulative frequency of the $m$th value, then it is usual to display the series graphically by plotting a graph of $x$, values of the $X_m$, against the reduced variate $y$ (von Mises, 1936) where

$y = -\log \log 1/F(x)$.†

The median value for $F(X_m)$ is given very closely by $(m-0.31)/(N+0.38)$, suggested by Chegodayev (1953), and this is a convenient value to use for plotting a graph of $x$ against $y$. The values of $X_1, X_2 \ldots X_N$ are plotted against the values of $y$ corresponding to

$$F(x) = \frac{0.69}{N+0.38}, \frac{1.69}{N+0.38}, \ldots \frac{N-0.31}{N+0.38}.$$

As an illustrative example we may take the data of ordered annual maximum 2 day falls of rain at Windsor, Berkshire, given in Table 2.1.

**Table 2.1** Annual maximum 2 day falls of rain (mm) at Windsor, Berkshire, 1893–1970.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 23.9 | 28.2 | 31.7 | 34.8 | 37.6 | 39.9 | 47.5 | 55.6 |
| 24.6 | 28.4 | 32.3 | 35.0 | 37.6 | 40.9 | 48.0 | 56.9 |
| 24.9 | 28.9 | 32.7 | 35.6 | 37.8 | 41.4 | 49.8 | 57.6 |
| 25.1 | 28.9 | 32.7 | 35.6 | 38.4 | 41.9 | 49.8 | 57.7 |
| 25.4 | 30.0 | 33.0 | 35.8 | 38.4 | 41.9 | 51.1 | 66.8 |
| 26.9 | 30.2 | 33.6 | 36.3 | 38.6 | 42.5 | 52.1 | 68.0 |
| 27.1 | 30.3 | 33.8 | 36.6 | 38.6 | 42.6 | 52.5 | 69.9 |
| 27.2 | 30.5 | 33.8 | 36.8 | 39.4 | 43.5 | 53.3 | 82.6 |
| 28.0 | 31.0 | 34.0 | 37.1 | 39.6 | 44.4 | 54.6 | |
| 28.0 | 31.0 | 34.8 | 37.4 | 39.9 | 47.2 | 55.3 | |

The annual maxima $x$ are contained in Table 2.1 and the values of the reduced variate $y$ are derived as explained above. The graph of the $x, y$ values is shown in Figure 2.1. A smooth curve can be drawn, and the return period $T(x)$ of any value $x$ can be read off at the appropriate value of $y$. An extreme value $x$ with return period $T$ has a probability $1/T$ of being equalled or exceeded in any one year, i.e.

†All logarithms are Napierian logarithms.

$$\frac{1}{T(x)} = 1-F(x) = 1-\exp(-e^{-y})$$

$$y = -\log\log\frac{T}{T-1} \doteqdot \log(T-0.5) \text{ for } T \gg 5.$$

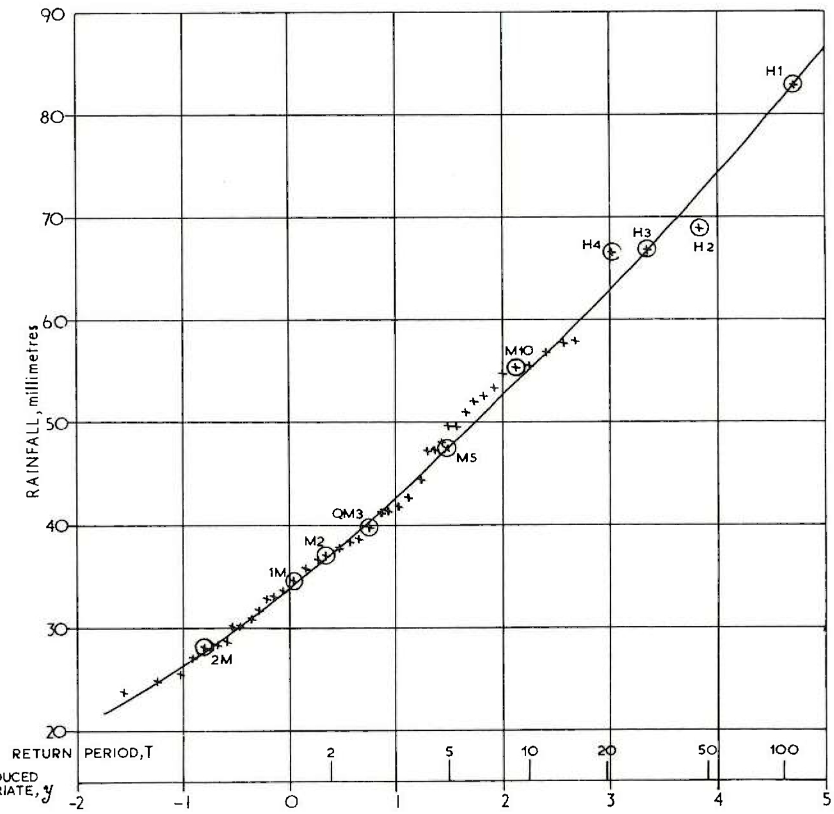



**Fig 2.1** Annual maximum 2 day falls of rain (mm) at Windsor, 1893–1970.

An excellent summary of the data, which may be used in a regional analysis, is made as follows. Divide the ordered data set into four quartiles. We can do this most simply by notionally taking each value four times, giving $4 \times 78 = 312$ values, and then dividing them into groups of 78. Take the quartile means, QM1, QM2, QM3 and QM4, here 27.8, 34.4, 40.0, 55.7. (For data of rainfall and flood discharge, which show proportional increases rather than additive increases, it is preferable to use geometric means in the quartile analysis, and the quartile means quoted are geometric means.) Take also the geometric mean of the middle half, i.e. the geometric mean of QM2 and QM3 = 37.1; and the geometric mean of the upper half, i.e. the geometric mean of QM3 and QM4 = 47.2. Note also the four highest values H4, H3, H2, H1, here 66.8, 68.0, 69.9, 82.6 mm.

The quartile means may be shown to have the following theoretical values for the reduced variate $y$ (e.g. Jenkinson, 1974). QM1 $y = -0.80$, QM2 $y = 0.02$, QM3 $y = 0.77$, QM4 $y = 2.32$. Middle half $y = 0.40$, upper half $y = 1.55$.

Analysis of many hundreds of sets of data showed good agreement with these theoretical results. The value of the reduced variate $y$ can also be related to various return periods as follows. The first quartile mean, QM1, is very close to the value, 2M, which occurs twice yearly in the partial duration series†, *viz.* $y = -\log 2 = -0.69$. The second quartile mean, QM2, is very close to the value 1M, which occurs once a year in the partial duration series, *viz.* $y = 0$. The mean of the middle half is very close to the value, M2, which occurs once in 2 years in the annual maximum series, *viz.* $y = -\log \log 2 = 0.37$. The mean of the upper half is very close to the value, M5, which occurs once in 5 years in the annual maximum series, *viz.* $y = -\log \log (5/4) = 1.50$. The fourth quartile mean, QM4, is very close to the value, M10, which occurs once in 10 years in the annual maximum series, *viz.* $y = -\log \log (10/9) = 2.25$.

The $y$ values for the quartile means vary with $N$, the number of observations. A summary is given in Table 2.2.

**Table 2.2** Quartile means for various sample sizes $N$.

| $N$ | QM1 | QM2 | QM3 | QM4 |
|---|---|---|---|---|
| 4 | −0.57 | 0.11 | 0.81 | 1.96 |
| 8 | −0.68 | 0.06 | 0.80 | 2.12 |
| 16 | −0.74 | 0.04 | 0.79 | 2.22 |
| 32 | −0.77 | 0.03 | 0.78 | 2.27 |
| ∞ | −0.80 | 0.02 | 0.77 | 2.32 |

The condensed information for Windsor, using geometric means for the quartiles, is given in Table 2.3. The four highest values are also included in this summary of the data. The geometric means and the four highest values are plotted in Figure 2.1; the reduced variate $y$ is the abscissa.

**Table 2.3** Quartile summary for 2 day annual maximum falls of rain at Windsor, 1893–1970.

| | | $x$(mm) | $y$ |
|---|---|---|---|
| QM1 | (≒2M) | 27.8 | −0.80 |
| QM2 | (≒1M) | 34.4 | 0.02 |
| QM3 | | 40.0 | 0.77 |
| QM4 | (≒M10) | 55.7 | 2.32 |
| Middle half | (≒M2) | 37.1 | 0.40 |
| Upper half | (≒M5) | 47.2 | 1.55 |
| H4 | | 66.8 | 3.03 |
| H3 | | 68.0 | 3.35 |
| H2 | | 69.9 | 3.83 |
| H1 | | 82.6 | 4.73 |

## 2.3 Combination of data sets

The paper by Jenkinson (1974) discusses fully the analysis of single sets of data. But it is obviously desirable for the present purpose to combine the large number of similar sets of data from different places into a regional set. The method used can be illustrated by data of annual 2 day maximum rainfall for England and Wales. The stations are grouped into suitable classes according to the magnitude of M5, the 5 year return period value, as indicated: (1) 40–50 mm, (2) 50–60 mm, (3) 60–75 mm, (4) 75–100 mm, (5) 100–150 mm, (6) 150–200 mm, (7) 200–300 mm.

For the first class, with 2 day M5 between 40 and 50 mm, there were 175 stations with an average period of record of 60 years. For each station, the quartile summary (geometric means) was set out, including the value of H1/M2, i.e. the highest value expressed as a proportion of the 2 year return period value, and noting $N$, the number of years of record, e.g. Windsor (from Table 2.3):

†The annual maximum series contains the largest value in each year. The partial duration series contains all values above a given threshold.

| $N$ | QM1 2M | QM2 1M | QM3 | QM4 M10 | Middle half M2 | Upper half M5 | H4 | H3 | H2 | H1 | H1/M2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 78 | 27.8 | 34.4 | 40.0 | 55.7 | 37.1 | 47.2 | 66.8 | 68.0 | 69.9 | 82.6 | 2.23 |

The values for all 175 stations were set out in the same way, and the median value (mean of the middle half in a quartile analysis) was obtained for each column. These are given in Table 2.4.

**Table 2.4** Median values (mm) for 175 stations (in England and Wales) with 2 day M5 40–50 mm.

| $N$ | QM1 2M | QM2 1M | QM3 | QM4 M10 | Middle half M2 | Upper half M5 | H4 | H3 | H2 | H1 | H1/M2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 59.6 | 27.59 | 34.13 | 40.41 | 54.48 | 37.17 | 47.25 | 60.36 | 63.69 | 69.45 | 80.58 | 2.170 |

The value of M2/M5 (median values) is 0.787; and this ratio was applied to each individual station value of H1/M2 to give a derived value of H1/M5. This procedure gives a more stable set of values of H1/M5 than is obtained by using the individual M5 values. For Windsor the stabilised value H1/M5 is actually (H1/M2) times the median value (M2/M5), i.e. $2.23 \times 0.787 = 1.75$.

A full quartile summary is now made of the set of 175 values of H1 and the stabilised values H1/M5. This is set out in Table 2.5.

**Table 2.5** Quartile analysis of H1 and stabilised H1/M5 for 2 day M5 in the range 40–50 mm (175 stations).

| | H1 (mm) | Stabilised H1/M5 | Standardised H1 (mm) |
|---|---|---|---|
| QM1 | 64.95 | 1.36 | 64.3 |
| QM2 | 75.86 | 1.60 | 75.5 |
| QM3 | 85.60 | 1.82 | 86.2 |
| QM4 | 111.32 | 2.41 | 114.1 |
| Middle half | 80.58 | 1.71 | 80.6 |
| Upper half | 97.62 | 2.10 | 99.2 |
| H4 | 154.2 | 3.59 | 169.6 |
| H3 | 165.6 | 3.61 | 170.7 |
| H2 | 166.3 | 3.64 | 172.2 |
| H1 | 201.4 | 4.65 | 219.8 |

The values of H1/M5 in the quartile analysis, Table 2.5, may be multiplied by the median value of M5 (= 47.25 mm in Table 2.4) to give standardised values of H1, to make allowance for the within-class variation in M5. These standardised H1 may be preferred to the actual values of H1, which are also set out in Table 2.5.

The analysis for England and Wales of annual maximum 2 day falls for stations with M5 between 40 and 50 mm is summarised in Tables 2.4 and 2.5. The median data of Table 2.4 may be plotted on an $x, y$ diagram with $y$ values for H4 to H1 appropriate to $N = 60$, *viz.* $y = 2.76, 3.09, 3.56, 4.47$. The curve may be called a 'growth curve' of rainfall with increasing return period $T$.

The quartile analysis of H1 in Table 2.5 can be used to extend the growth curve to higher return periods. By the definition of return period $T$, the cumulative proportion $F$ in the ordered set of 175 values of H1 (we may imagine also an infinite set of values of H1) is given by

$$F = \left(1 - \frac{1}{T}\right)^N$$

where $N$ is the median number of years of record, regarding as unimportant the slight variability in $N$. The return period $T$ is given by

$T = 1/(1-F^{1/N})$.

For example, if we interpolate at the 37, 50, 80, 90 % points in our ordered array of absolute extremes H1, i.e. $F = 0.37, 0.50, 0.80, 0.90$, then the interpolated maxima correspond to return periods

$T = 60.8, 87.1, 269.4, 570.0$.

More generally for sufficiently large $N$ we have $T = N, 1.45N, 4.5N, 9.5N$, for $F = 37, 50, 80, 90$ % respectively. Thus, for example, the median value ($F = 50$ %) of H1 values in $N = 60$ year records has a return period $T = 1.45N$, i.e. 87 years. These four percentage points ($F = 37, 50, 80, 90$ %) in the frequency distribution of H1 correspond to the values of H1 in Table 2.5 for QM2, middle half, upper half, QM4, *viz.* 75.9, 80.6, 97.6, 111.3 (or the standardised values in the third column). So these values can be plotted at values of $y = \log(T-0.5)$ where $T = 60, 87, 270, 570$, since $N = 60$. The second of these values is of course identical with the median value for H1. The three remaining values are plotted in Figure 2.2 to confirm and extend the growth curve (curve c).

If the network of stations used for the regional analysis is not too close, the four highest values in the H1 array in Table 2.5 may be regarded as the upper members of a set of $N' = 175 \times 60$, i.e. $N' = 10\ 500$ annual maxima.

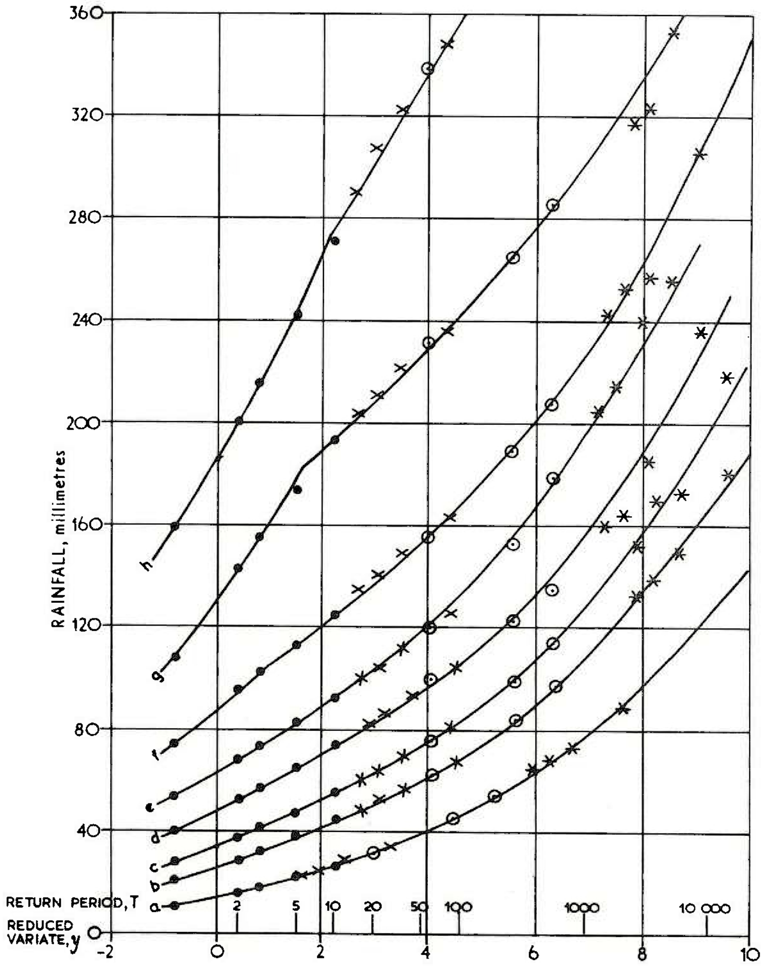



**Fig 2.2** Rainfall growth curves. England and Wales. a, 2 hour rainfall; b, 1 day rainfall for M5 30–40 mm; c, 2 day rainfall for M5 40–50 mm; d, 1 day rainfall for M5 60–75 mm; e, 4 day rainfall for M5 75–100 mm; f, 8 day rainfall for M5 100–150 mm; g, 25 day rainfall for M5 150–200 mm; h, 8 day rainfall for M5 200–300 mm.

These may be plotted, with lesser confidence, to extend further the growth curve. The appropriate median plotting points for large $N'$, the total number of values, are respectively

$$\begin{aligned} y = \log N' - 1.31 &= 7.95 \\ \log N' - 0.99 &= 8.27 \\ \log N' - 0.52 &= 8.74 \\ \log N' + 0.37 &= 9.63 \end{aligned}$$

(see Section 2.5 for a derivation of these values).

The completed regional summary is plotted in Figure 2.2. The quartile values are shown as points, the median H4 to H1 as crosses, the quartiles of the H1 array as circles, and the four upper values as stars.

By taking different ranges of M5 for each duration, and then repeating the operation for each duration from 15 seconds to 25 days, a set of growth curves can be compiled which can be used as standard curves for given M5 values. Alternatively, and more simply, the ratios of $MT/M5$, where $MT$ is the maximum with return period $T$ years, can be compiled for given values of M5.

It was found that there were small but detectable differences between the sets of growth curves for England and Wales, and Scotland and Northern Ireland, and these were treated as two different regions. But with-

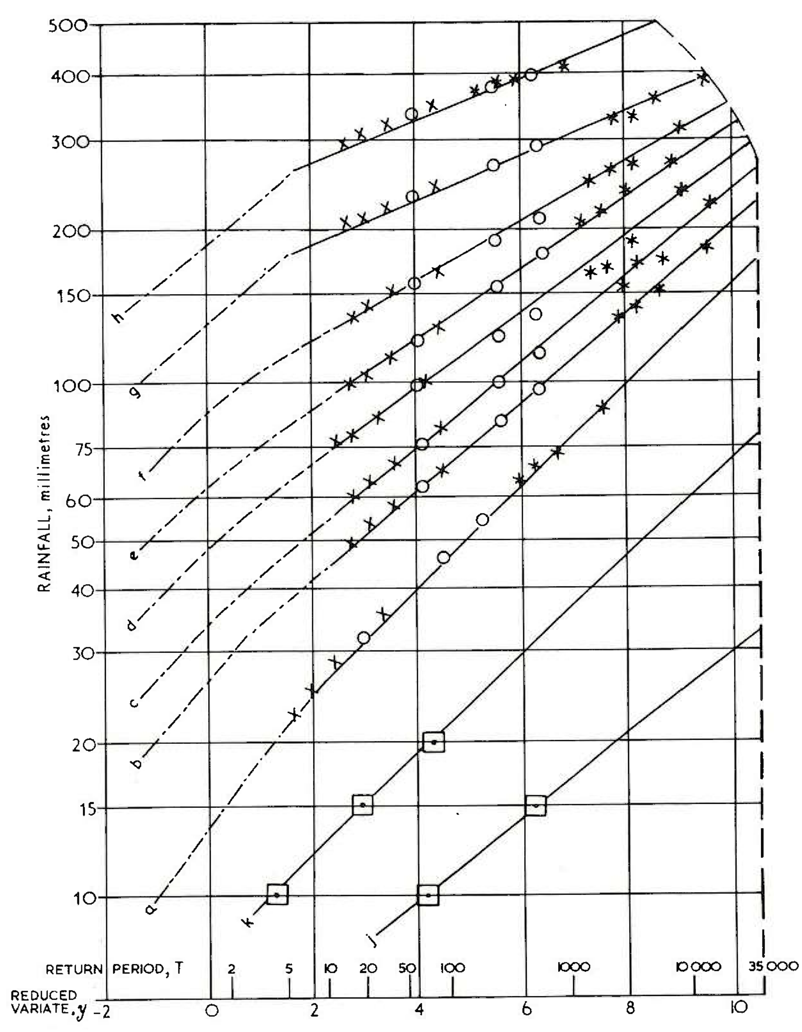



Fig 2.3 Rainfall growth curves. England and Wales. a–h, as Figure 2.2; j, 5 minute rainfall; k, 15 minute rainfall.

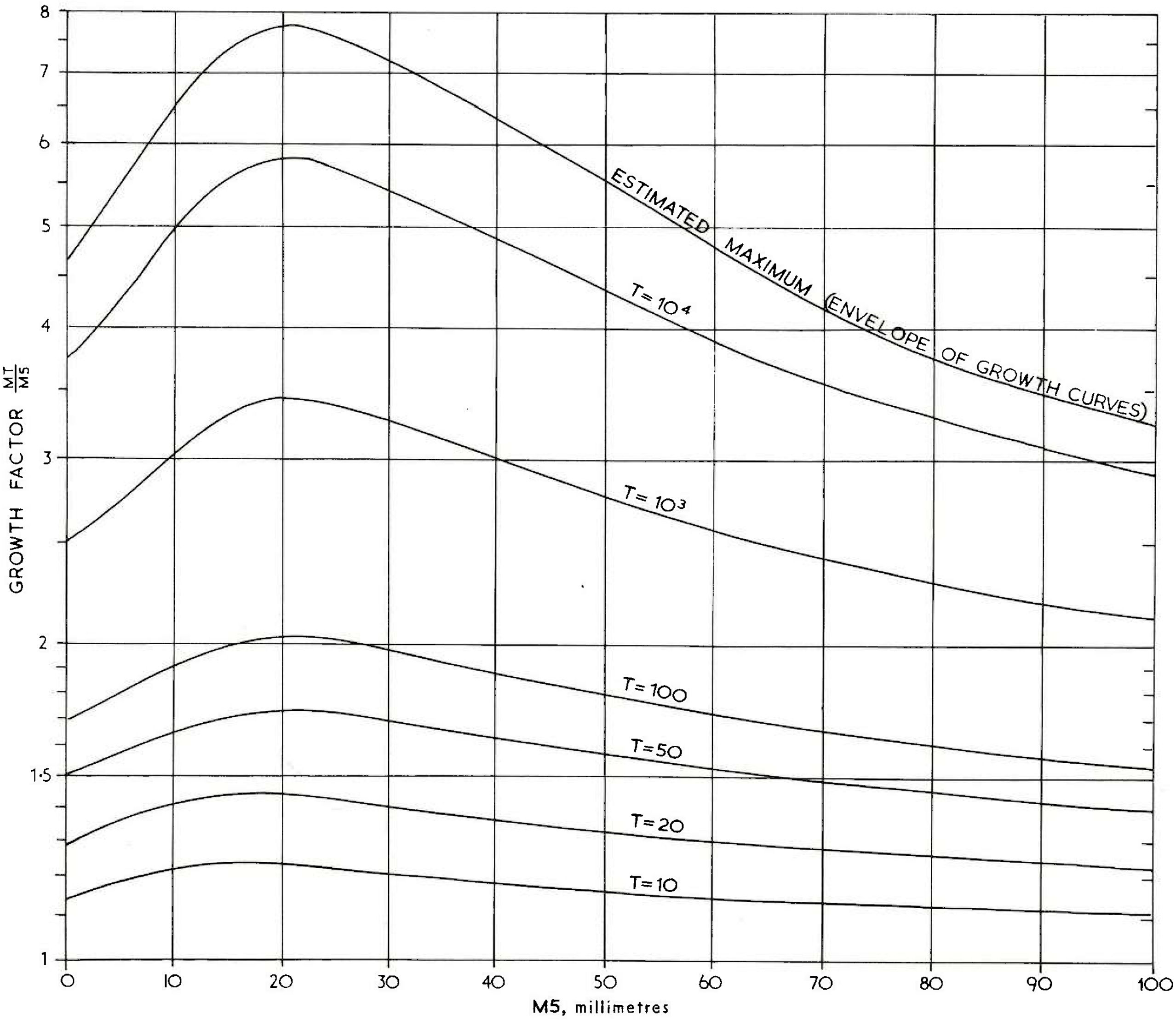
need also to describe frequency curve (mm, not dimensionless).

in a region, the growth curve for a specified duration at a given place is determined by the M5 value. Figure 2.2 shows a small subset of the many growth curves prepared for England and Wales. They are: a, 2 hour rainfall; b, 1 day rainfall for M5 in the range 30–40 mm; c, 2 day rainfall for M5 40–50 mm; d, 1 day rainfall for M5 60–75 mm; e, 4 day rainfall for M5 75–100 mm; f, 8 day rainfall for M5 100–150 mm; g, 25 day rainfall for M5 150–200 mm; h, 8 day rainfall for M5 200–300 mm.

Other growth curves prepared for different durations from 15 seconds (from Jardi rate of rainfall records) to 25 days take their place within a system of similar curves, each categorised simply by the M5 value. The growth curves suggest that the relation between M$T$ and M5 is of the form: M$T$/M5 is proportional to $T^c$.

This is shown more clearly when the curves are plotted as $x$, $y$ diagrams with $x$ on a logarithmic scale. The subset of Figure 2.2 is plotted in this way in Figure 2.3, with median curves for 5 and 15 minutes also added. They show that for $T \geq 5$ the growth curves are essentially straight lines, with slope $c$ varying systematically. The growth curves for England

**Fig 2.4** Growth factors M$T$/M5 for rainfall over England and Wales.



and Wales can be expressed quite closely by the relation log ($MT/M5$) = $c\,(y-1.5)$ where the related values of $c$ and M5 are given in Table 2.6.

| M5 (mm) | $c$ | M5 (mm) | $c$ |
|---|---|---|---|
| 0.5 | 0.171 | 40 | 0.205 |
| 2 | 0.175 | 50 | 0.191 |
| 5 | 0.185 | 75 | 0.160 |
| 10 | 0.209 | 100 | 0.139 |
| 15 | 0.222 | 150 | 0.119 |
| 20 | 0.228 | 200 | 0.108 |
| 25 | 0.225 | 500 | 0.077 |
| 30 | 0.219 | 1000 | 0.066 |

**Table 2.6** Generalised $c$, M5 relation for rainfall growth curves, England and Wales.

Too much stress however need not be placed on these relations; the growth curves for the region have been determined from the data, although the relation was used to effect a little smoothing. The ratio $MT/M5$ may be termed the 'growth factor'. The growth factors for England and Wales are shown in Figure 2.4, for M5 less than 100 mm; and are given more fully in Table 2.7. The method of presentation is to give the values of the ratio $MT/M5$, for various return periods $T$, as a function of M5. For return periods below 5 years, direct analysis of records should provide better estimates.

| M5 | Partial duration series | | Annual maximum series | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (mm) | 2M | 1M | M2 | M10 | M20 | M50 | M100 | M1000 | M10 000 |
| 0.5 | 0.52 | 0.67 | 0.76 | 1.14 | 1.30 | 1.51 | 1.70 | 2.52 | 3.76 |
| 2 | 0.49 | 0.65 | 0.74 | 1.16 | 1.32 | 1.53 | 1.74 | 2.60 | 3.94 |
| 5 | 0.45 | 0.62 | 0.72 | 1.18 | 1.35 | 1.56 | 1.79 | 2.75 | 4.28 |
| 10 | 0.43 | 0.61 | 0.70 | 1.21 | 1.41 | 1.65 | 1.91 | 3.09 | 5.01 |
| 15 | 0.46 | 0.62 | 0.70 | 1.23 | 1.44 | 1.70 | 1.99 | 3.32 | 5.54 |
| 20 | 0.50 | 0.64 | 0.72 | 1.23 | 1.45 | 1.73 | 2.03 | 3.43 | 5.80 |
| 25 | 0.52 | 0.66 | 0.73 | 1.22 | 1.43 | 1.72 | 2.01 | 3.37 | 5.67 |
| 30 | 0.54 | 0.68 | 0.75 | 1.21 | 1.41 | 1.70 | 1.97 | 3.27 | 5.41 |
| 40 | 0.56 | 0.70 | 0.77 | 1.18 | 1.37 | 1.64 | 1.89 | 3.03 | 4.86 |
| 50 | 0.58 | 0.72 | 0.79 | 1.16 | 1.33 | 1.58 | 1.81 | 2.81 | 4.36 |
| 75 | 0.63 | 0.76 | 0.81 | 1.13 | 1.27 | 1.47 | 1.64 | 2.37 | 3.43 |
| 100 | 0.64 | 0.78 | 0.83 | 1.12 | 1.24 | 1.40 | 1.54 | 2.12 | 2.92 |
| 150 | 0.64 | 0.78 | 0.84 | 1.11 | 1.21 | 1.33 | 1.45 | 1.90 | 2.50 |
| 200 | 0.64 | 0.78 | 0.84 | 1.10 | 1.30 | 1.30 | 1.40 | 1.79 | 2.30 |
| 500 | 0.65 | 0.79 | 0.85 | 1.09 | 1.15 | 1.20 | 1.27 | 1.52 | — |
| 1000 | 0.66 | 0.80 | 0.86 | 1.07 | 1.12 | 1.18 | 1.23 | 1.42 | — |

**Table 2.7** Growth factors $MT/M5$ for England and Wales.

The generalised $c$, M5 relation for Scotland and Northern Ireland is given in Table 2.8; and the growth factors for the region are given in Table 2.9.

| M5 (mm) | $c$ | M5 (mm) | $c$ |
|---|---|---|---|
| 0.5 | 0.171 | 40 | 0.205 |
| 2 | 0.175 | 50 | 0.191 |
| 5 | 0.185 | 75 | 0.160 |
| 10 | 0.209 | 100 | 0.139 |
| 15 | 0.222 | 150 | 0.119 |
| 20 | 0.228 | 200 | 0.108 |
| 25 | 0.225 | 500 | 0.077 |
| 30 | 0.219 | 1000 | 0.066 |

**Table 2.8** Generalised $c$, M5 relation for rainfall growth curves, Scotland and Northern Ireland.

| M5 (mm) | Partial duration series 2M | 1M | M2 | M10 | Annual maximum series M20 | M50 | M100 | M1000 | M10 000 |
|---|---|---|---|---|---|---|---|---|---|
| 0.5 | 0.55 | 0.68 | 0.76 | 1.14 | 1.30 | 1.51 | 1.71 | 2.54 | 3.78 |
| 2 | 0.55 | 0.68 | 0.76 | 1.15 | 1.31 | 1.54 | 1.75 | 2.65 | 4.01 |
| 5 | 0.54 | 0.67 | 0.76 | 1.16 | 1.34 | 1.62 | 1.86 | 2.94 | 4.66 |
| 10 | 0.55 | 0.68 | 0.75 | 1.18 | 1.38 | 1.69 | 1.97 | 3.25 | 5.36 |
| 15 | 0.55 | 0.69 | 0.75 | 1.18 | 1.38 | 1.70 | 1.98 | 3.28 | 5.44 |
| 20 | 0.56 | 0.70 | 0.76 | 1.18 | 1.37 | 1.66 | 1.93 | 3.14 | 5.12 |
| 25 | 0.57 | 0.71 | 0.77 | 1.17 | 1.36 | 1.64 | 1.89 | 3.03 | 4.85 |
| 30 | 0.58 | 0.72 | 0.78 | 1.17 | 1.35 | 1.61 | 1.85 | 2.92 | 4.60 |
| 40 | 0.59 | 0.74 | 0.79 | 1.16 | 1.33 | 1.56 | 1.77 | 2.72 | 4.16 |
| 50 | 0.60 | 0.75 | 0.80 | 1.15 | 1.30 | 1.52 | 1.72 | 2.57 | 3.85 |
| 75 | 0.62 | 0.77 | 0.82 | 1.13 | 1.26 | 1.45 | 1.62 | 2.31 | 3.30 |
| 100 | 0.63 | 0.78 | 0.83 | 1.12 | 1.24 | 1.40 | 1.54 | 2.12 | 2.92 |
| 150 | 0.64 | 0.79 | 0.84 | 1.10 | 1.20 | 1.33 | 1.45 | 1.90 | 2.50 |
| 200 | 0.65 | 0.80 | 0.85 | 1.09 | 1.18 | 1.30 | 1.40 | 1.79 | 2.30 |
| 500 | 0.66 | 0.80 | 0.86 | 1.08 | 1.14 | 1.20 | 1.27 | 1.52 | — |
| 1000 | 0.66 | 0.80 | 0.86 | 1.07 | 1.12 | 1.18 | 1.23 | 1.42 | — |

**Table 2.9** Growth factors M*T*/M5 for Scotland and Northern Ireland.

## 2.4 Growth factors for maxima recorded within a given month or season

Monthly and seasonal rainfall maxima with 5 year return period were derived for various durations. The results are presented in Chapter 3, Section 3.4. Given the 5 year return period value for any month it remains to compute the $T$ year return period value. As with annual maxima this problem is overcome by constructing regional growth curves and compiling regional growth factors M$T$/M5.

Growth curves for return periods between 5 and 100 years were prepared for 2 hour, 2 day and 25 day durations for monthly and seasonal maxima, and these were compared with the corresponding growth curves for annual maxima. The comparison showed that, roughly speaking, the monthly and seasonal growth factors are similar to the annual growth factors, but the differences could be considered significant. For example, if the January M5 value is 60% of M5 for annual maxima, so also the January M100 value will also be approximately 60% of M100 for annual maxima. The correct percentage is in fact 68%. A summary is given in Table 2.10 of the M5 and M100 monthly rainfall values, expressed as percentages of the annual M5 and M100 values respectively.

Similar relationships for seasonal M5 and M100 values are given in Table 2.11. The monthly and seasonal M5 values are given as a percentage of the M5 for annual maxima in Table 3.9.

The individual months are considered as two groups, those months during winter (November to April) and those during summer (May to October). The analysis did not justify consideration of different relationships for each of the different months.

Table 2.10 Relationship between the M5 and M100 monthly values (both M5 and M100 values are expressed as percentages of the annual M5 and M100 values respectively).

| M5 percentage | M100 percentage: Individual months (Nov. to April) | M100 percentage: Individual months (May to Oct.) |
|---|---|---|
| 20 | 17 | — |
| 30 | 28 | — |
| 40 | 40 | 46 |
| 50 | 54 | 60 |
| 60 | 68 | 73 |
| 70 | 80 | 84 |
| 80 | 89 | 92 |
| 90 | — | — |

Example: If the January M5 value is 60% of the M5 for annual maxima then the January M100 value is 68% of M100 for the annual maxima.

Table 2.11 Relationship between the M5 and M100 seasonal values (both M5 and M100 values are expressed as percentages of the annual M5 and M100 values respectively).

| M5 percentage | M100 percentage: Winter season (Nov. to April) | M100 percentage: Summer season (May to Oct.) |
|---|---|---|
| 20 | — | — |
| 30 | — | — |
| 40 | 30 | — |
| 50 | 40 | — |
| 60 | 50 | — |
| 70 | 63 | 70 |
| 80 | 78 | 84 |
| 90 | 92 | 96 |

Example: If the winter season M5 value is 60% of M5 for the annual maxima then the winter season M100 value is 50% of M100 for the annual maxima.

## 2.5 Appendix: *a derivation of a simplified formula for the reduced variate y*

To derive a simplified formula for obtaining values of the reduced variate $y$ corresponding to the four highest values in a set of annual maxima containing a very large number of members, given

$$y = -\log\log 1/F(x)$$

and

$$F(x) = \frac{M-0.31}{N+0.38}$$

where $M$ is the $m$th value of a series of ordered annual maxima with $N$ members. Let $M = N+1-k$ so that $k=1$, 2, 3, 4 for the four highest members, then

$$F(x) = \frac{N+0.69-k}{N+0.38}$$

and

$$\log\frac{1}{F(x)} = \log\frac{N+0.38}{N+0.69-k}.$$

For $k = 1$, 2, 3 or 4 and very large values of $N$ we may write,

$$\log\frac{N+0.38}{N+0.69-k} = \log(1+x) = x+O(x^2) \doteqdot x \text{ where } 0 \leq x \ll 1.$$

Also as

$$\frac{N+0.38}{N+0.69-k} = 1+x$$

then

$$x = \frac{k-0.31}{N+0.69-k} \doteqdot \frac{k-0.31}{N} \qquad \text{if } k \ll N.$$

Since

$$y = -\log \log \frac{1}{F(x)}$$

$$y = -\log \log \frac{N+0.38}{N+0.69-k}$$

and it follows from the above that

$$y \doteqdot -\log x \doteqdot -\log \frac{k-0.31}{N}.$$

Therefore, for small positive integer values of $k$ and very large values of $N$ a simplified formula for $y$ is given by

$$y = \log N - \log (k-0.31).$$

For example, the value of the reduced variate $y$ for the largest member of a series of annual maxima is

$\log N - \log 0.69$. When $N = 10500$, $y = 9.63$.

### 2.6 Suggestions for further reading

MISES R. VON (1936) La distribution de la plus grande de *n* valeurs. *Revue mathematique de l'Union Interbalkanique (Athens)* **1**, 1.

CHEGODAYEV N. N. (1953) Computation of runoff on small catchments. *Transzhedorizdat, Moscow.*

# 3 Estimation and mapping of M5 (5 year) values for different durations

## 3.1 Summary

M5 values of 1, 2, 4, 8 and 25 day rainfall were estimated for more than 600 stations with an average of 60 years of record; and these were supplemented by estimates of 2 day M5 and 25 day M5 from an additional 6000 stations using data for 1961–70. Estimates of average annual rainfall, AAR, for the period 1941–70, were also obtained for each station. Then, using estimates for nearly 7000 stations, maps were prepared of AAR (Figure 3.1†); 2 day M5 (Figure 3.2†); the ratio (2 day M5)/AAR (Figure 3.3†); and the ratio (25 day M5)/AAR (Figure 3.4†). Linking relations to provide estimates of M5 for durations of 48, 72 and 96 hours are given in Table 3.2. For other durations ($D$) the best estimates of M5 rainfall are obtained by linear interpolation on a diagram of log M5 against log $D$. An initial quick estimate of M5 rainfall for various durations between 24 hours and 25 days is desirable for some purposes. Such estimates are given in Tables 3.3 and 3.4.

M5 values of 60 minute rainfall were estimated for approximately 200 recording raingauge stations; 101 of these stations had 20 years or more of records. Regional relations were found linking the ratio $r$ = (60 minute M5)/(2 day M5) with $w$, the M5 value of precipitable water (Figure 3.8); with $t$ the number of days per year with thunder (Figure 3.9); and with 2 day M5. These relations were used to provide estimates of $r$ and also 60 minute M5 for a network of 1000 points. A map of $r$ is given in Figure 3.5† and a map of 60 minute M5 has been prepared on the same scale, and is obtainable from the Meteorological Office (hydrometeorological branch) on request. A broad guide to 60 minute M5 values is given in Figure 3.6.

Corresponding to each value of $r$, the ratio M5($D$)/(M5(2 day)) is defined for any duration $D$ from 60 minutes to 48 hours. These relations linking M5 for these durations are given in Table 3.7. A broad guide to the values of 6 hour M5 is given in Figure 3.7.

Relations giving M5 for durations less than 60 minutes as a percentage of 60 minute M5 are given in Table 3.6.

Values of M5 for monthly and seasonal maxima for durations from 1 hour to 25 days, expressed as percentages of the corresponding M5 for annual maxima, are given in Table 3.9.

## 3.2 Estimation of M5 for durations of 24 hours to 25 days

For the 600 stations with an average of 60 years of record, M5 values for 1, 2, 4, 8 and 25 days were estimated by extreme value analysis, using maximum likelihood estimation of Jenkinson (1974). These estimates confirmed the excellence of the quartile estimates of M5 and of M10. Quartile or other similar analysis, e.g. sextile analysis (Jenkinson, 1969), gives accurate estimates of 2M (twice a year), 1M (once a year), and M2.

Quartile analysis was made for 2 day monthly and seasonal data, and for 1, 4, 8 day seasonal data, and for the recording raingauge data. The 25 day M5 values mentioned above were in fact obtained from data of annual calendar month maxima, RC. By comparison with 20, 25 and 30 day values of M5 for a number of stations, it was found that calendar month M5 was close to 25 day M5.

By comparison with M5 values for stations with hourly data, the equivalent durations for M5 values for 1, 2, 4, 8 rainfall days were found;

†The following maps illustrating Volume II are to be found in Volume V.

| Figure | | |
|---|---|---|
| 3.1 | (N) | Average annual rainfall, 1941–70, (North Britain) |
| 3.1 | (S) | Average annual rainfall, 1941–70, (South Britain) |
| 3.1 | (NI) | Average annual rainfall, 1941–70, (Northern Ireland) |
| 3.1 | (I) | Average annual rainfall, 1931–60, (Ireland) |
| 3.2 | (N) | 2 day M5 rainfall, (North Britain) |
| 3.2 | (S) | 2 day M5 rainfall, (South Britain) |
| 3.2 | (I) | 2 day M5 rainfall, (Ireland) |
| 3.3 | (N) | 2 day M5 rainfall as percent of AAR, (North Britain) |
| 3.3 | (S) | 2 day M5 rainfall as percent of AAR, (South Britain) |
| 3.3 | (I) | 2 day M5 rainfall as percent of AAR, (Ireland) |
| 3.4 | | 25 day M5 rainfall as percent of AAR, (British Isles) |
| 3.5 | (N) | 60 minute M5 rainfall as percent of 2 day M5, (North Britain) |
| 3.5 | (S) | 60 minute M5 rainfall as percent of 2 day M5, (South Britain) |
| 3.5 | (I) | 60 minute M5 rainfall as percent of 2 day M5, (Ireland) |

but since these durations vary with AAR it was found to be simpler, and quite accurate, to assign constant multiplying factors to the M5 values to give M5 values for 24, 48, 96, 192 hours respectively. These are given in Table 3.1.

**Table 3.1** Multiplying factors to give M5 equivalents for rainfall days.

| Rainfall days | 1 | 2 | 4 | 8 |
|---|---|---|---|---|
| Multiplying factor | 1.11 | 1.06 | 1.03 | 1.015 |
| Rainfall hours | 24 | 48 | 96 | 192 |

### *3.2.1 Mapping of 2 day M5 and 25 day M5*

From the 600 long period stations (average 60 years) estimates of 2 day M5, 25 day M5 and AAR (1941–70) were obtained for each station, and the ratios (2 day M5)/AAR and (25 day M5)/AAR. The stations with more than 100 years of record included Kew (1871–1970), Oxford (1853–1970), Stonyhurst College, Lancs. (1871–1970), and Armagh, Northern Ireland (1854–1970).

Daily rainfall amounts for 5000 additional stations were available on magnetic tape for the period 1961–70; and a further 1000 monthly recording stations had monthly totals on magnetic tape for 1961–70. Estimates of long period 2 day and 25 day M5 were obtained for each of these 6000 stations, that is, estimates of the values which would have been obtained from 60 years of daily records.

The method used was as follows. For all 600 long period stations, the 1961 2 day maximum fall was recorded as a proportion, $p$, of the long period 2 day M5. Isopleths were drawn for 1961 on a large scale map of the United Kingdom, and a value of $p$ interpolated for a given short period (1961–70) station whose 2 day maximum fall for 1961 is R2. Then an estimate for the long period 2 day M5 was R2/$p$. The median value of the estimates obtained from the available records for 1961–70 was taken as the final estimate for the long period (1911–70) 2 day M5. The standard error of estimate is 3–4% for a 10 year record, but even a 4 year record gives a good estimate.

The long period 25 day M5 was similarly taken as the median value of estimates RC/$q$, where RC is a short period station calendar month maximum value for a given year and $q$ the corresponding interpolated proportion of long period 25 day M5.

Estimates of long period 2 day M5 for stations with only monthly records were obtained from the median value of estimates RC/$Q$, where $Q$ is an interpolated proportion from maps of RC/(long period 2 day M5). Tests on high altitude stations with daily records have shown that these estimates from monthly records are very good. They are in fact to be preferred to those from the daily records in areas where many of the adjoining stations are monthly recording stations.

Estimates of 1941–70 AAR were obtained from the median of estimates AR/$P$, where AR is a short period station annual rainfall total, and $P$ the corresponding interpolated proportion of AAR. For simplicity in outlining the method, graphical methods have been described for interpolating values of $p$, $q$, $Q$, $P$ etc. for each of 6000 stations from each of 10 annual maps; but of course a computerised method was used. The method adopted to find interpolated values at a given short period station was to fit a plane surface to the nearest six long period station values, with inverse square weighting $1/d^2$ where $d$ is the distance of a station.

Values were transformed logarithmically before fitting the plane surface, since the gradients increase proportionately rather than additively. If all stations within a minimum distance $d_0$ are weighted as if they were at distance $d_0$, then a degree of smoothing is effected, and the inverse distance weighting is less severe than the square of the distance. (If $d_0$ is large enough, all stations have equal weight, irrespective of distance.) A value of 5 km for $d_0$ was chosen for this work.

From the 7000 station values, maps were plotted and drawn up for AAR (Figure 3.1); 2 day M5 (Figure 3.2); the ratio (2 day M5)/AAR (Figure 3.3) and the ratio (25 day M5)/AAR (Figure 3.4). Values of 2 day M5 can be read directly from Figure 3.2; or in areas of large gradient the ratio (2 day M5)/AAR can be read from Figure 3.3, and used in conjunction with AAR. The values of 25 day M5 are only given as percentages of AAR.

### 3.2.2 *Estimates of M5 values for duration 2–25 days*

Suppose that 2 day M5 and 25 day M5 have been determined from Figures 3.2–3.4, and AAR from Figure 3.1. Then the best estimate of 24 hour M5 is found from relations between 60 minute M5 and 2 day M5, as given in Table 3.7, described fully in Section 3.3, or identically from Section 3.6. But a rapid initial estimate, with some slight loss in accuracy, is given in Table 3.3 (from values of 2 day M5 and AAR); and a rough estimate can be made from Table 3.4 (from a value of AAR alone).

The best estimate for 48 hour M5 is taken to be 1.06 times 2 day M5 (Table 3.1). The best estimate for 96 hour M5 is found by relating the ratio (4 day M5)/(2 day M5) to AAR, and then by converting 4 day M5 to 96 hour M5 by multiplying by the factor 1.03 (Table 3.1). See Table 3.2 for a summary of the relation. The best estimate for 72 hour M5 is taken as the geometric mean of 48 hour M5 and 96 hour M5. For durations $D$ between 96 hours and 25 days the best estimates of M5 are obtained by linear interpolation on a diagram of log M5 against log $D$.

Table 3.2 gives a summary of the relations which are found to give the best estimates of 48 hour M5, 72 hour M5 and 96 hour M5, from values of 2 day M5 and AAR.

**Table 3.2** Relations giving best estimates of 48 hour M5, 72 hour M5 and 96 hour M5, from 2 day M5 and AAR.

| AAR (hundreds of mm) | 5–6 | 6–8 | 8–10 | 10–14 | 14–20 | 20–28 | 28–40 | 40– |
|---|---|---|---|---|---|---|---|---|
| (48 hour M5)/(2 day M5) | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 |
| (72 hour M5)/(2 day M5) | 1.16 | 1.17 | 1.19 | 1.20 | 1.21 | 1.22 | 1.23 | 1.25 |
| (96 hour M5)/(2 day M5) | 1.26 | 1.29 | 1.33 | 1.36 | 1.38 | 1.40 | 1.43 | 1.47 |

It is emphasised once more that the best estimate of 25 day M5 is to be obtained from Figures 3.2–3.4; the best estimate of 192 hour M5 by interpolation between 96 hour M5 and 25 day M5; and the best estimate of 24 hour M5 is to be taken from Table 3.7, or identically from Section 3.6.

### 3.2.3 *Initial quick estimates of M5 and M100 for durations 24 hours to 25 days*

Initial quick estimates, with some slight loss in accuracy, for 24 hour M5, 192 hour M5 and 25 day M5, may be obtained from relations similar to those which gave the best estimate for 96 hour M5, and these are given in Table 3.3.

**Table 3.3** Relations between (given duration M5)/(2 day M5) and AAR for $D$ = 24 hours, 192 hours, 25 days.

| AAR (hundreds of mm) | 5–6 | 6–8 | 8–10 | 10–14 | 14–20 | 20–28 | 24–40 | 40– |
|---|---|---|---|---|---|---|---|---|
| (24 hour M5)/(2 day M5) | 0.90 | 0.88 | 0.85 | 0.82 | 0.80 | 0.79 | 0.77 | 0.73 |
| (192 hour M5)/(2 day M5) | 1.62 | 1.68 | 1.79 | 1.89 | 1.95 | 2.00 | 2.06 | 2.12 |
| (25 day M5)/(2 day M5) | 2.58 | 2.88 | 3.16 | 3.56 | 3.84 | 3.91 | 3.96 | 4.02 |

To enable the reader to get a broad initial picture of the general level of values of M5 for durations 1 day to 25 days over the United Kingdom, a greatly simplified relation between AAR and 2 day M5 is presented in Table 3.4. Then, using the relations of Tables 3.2 and 3.3, Table 3.4 also presents the much simplified scheme of M5 values for 24 ,48, 72, 96, 192 hours and 25 days corresponding to the given AAR.

From Tables 2.7 and 2.9 mean growth factors for the United Kingdom for $T$ = 100 were obtained, and these when applied to the simplified set of M5 values gave a simplified set of 100 year values M100. These are also given in Table 3.4. It should be emphasised that the values in the table may be as much as 20% in error for some durations in some areas. The table should therefore only be used as a broad initial guide to the expected magnitudes of M5 and M100 values for durations 1–25 days for different rainfall bands in the United Kingdom.

**Table 3.4** Scheme for obtaining initial approximate values of M5 and M100 for durations 24 hours to 25 days, from a knowledge only of AAR.

| AAR (hundreds of mm) | Approximate 2 day M5 (mm) | Approximate M5 and M100 values (mm) for durations: 24 h | 48 h | 72 h | 96 h | 192 h | 25 days |
|---|---|---|---|---|---|---|---|
| 5–6 | 44 | 40 | 47 | 51 | 55 | 71 | 114 |
| | | 73 | 84 | 90 | 96 | 118 | 171 |
| 6–8 | 50 | 44 | 53 | 59 | 65 | 84 | 144 |
| | | 80 | 93 | 101 | 110 | 134 | 209 |
| 8–10 | 59 | 50 | 63 | 70 | 78 | 106 | 186 |
| | | 89 | 107 | 116 | 126 | 161 | 262 |
| 10–14 | 71 | 58 | 75 | 85 | 97 | 134 | 253 |
| | | 100 | 123 | 135 | 150 | 196 | 344 |
| 14–20 | 92 | 74 | 98 | 111 | 127 | 179 | 353 |
| | | 121 | 152 | 168 | 188 | 254 | 462 |
| 20–28 | 124 | 98 | 131 | 151 | 174 | 248 | 485 |
| | | 152 | 193 | 219 | 247 | 340 | 616 |
| 28–40 | 177 | 136 | 188 | 218 | 253 | 365 | 701 |
| | | 199 | 265 | 303 | 344 | 478 | 876 |
| 40– | 211 | 158 | 224 | 262 | 306 | 441 | 842 |
| | | 228 | 309 | 356 | 410 | 564 | 1044 |

Table 4.3 in Chapter 4 gives a similar scheme for obtaining initial approximate values for estimates of maximum rainfall for these durations, given only AAR.

## 3.3 Best estimation of M5 for durations less than 2 days

### *3.3.1 Data analysed*

*a* Annual frequencies exceeding 5, 10, 15, 20 and 25 mm in durations of 5, 10, 15, 30, 60, 120, 240, 480 minutes for 150 stations (Jackson & Larke, 1974).
*b* Monthly and annual maximum falls for durations 1, 2, and 6 clock hours for 100 stations, 50 of which are in set *a*.
*c* Summer maximum falls for durations 2, 4, 10, 30, 60 minutes at Cardington and Winchcombe. At each of these places a network of about 20 recording gauges within an area of 10–20 $km^2$ was maintained for 6 years.
*d* Monthly and annual maximum instantaneous (15 second) rates of rainfall from Jardi rate of rainfall recorders maintained at Kew, Eskdalemuir, Aberdeen and Valentia.

These data were used to construct growth curves as described in Chapter 2 and also to obtain M5 estimates for each duration, and monthly and seasonal M5 estimates where possible.

### *3.3.2 Mapping of 60 minute M5*

By comparison of M5 estimates from the 50 stations common to data sets *a* and *b* of 3.3.1, constant multiplying factors were found to convert M5 values for 1, 2, 6 clock hours into M5 values for 60, 120, 360 minutes (Table 3.5). A duration of 1 hour is any period of 60 minutes whereas 1 clock hour is 1 hour beginning at a main hour, i.e. 0300 to 0400 GMT.

**Table 3.5** Multiplying factors to give M5 equivalents for clock hours.

| Clock hours | 1 | 2 | 6 |
|---|---|---|---|
| Multiplying factor | 1.15 | 1.06 | 1.015 |
| Minutes | 60 | 120 | 360 |

From the analyses, approximately 200 values of 60 minute M5 were obtained, a rather sparse covering for the United Kingdom. As would be expected, relatively high 60 minute falls occur in the areas of frequent thunderstorms (Figure 3.9) and high values of precipitable water content (Figure 3.8). It was thus possible to find efficient relations for estimating 60 minute M5, or rather the ratio $r$ = (60 minute M5)/(2 day M5), from $w$, the M5 value of precipitable water (Figure 3.8), $t$, the number of days per year with thunder (Figure 3.9) and 2 day M5. Separate relations were obtained for Scotland and for England, Wales and Ireland.

From these relations, estimates of the ratio $r$ were obtained for points of an equally spaced network of 1000 points, and also values of 60 minute M5. These were mapped and drawn up in Figures 3.5 and 3.6 respectively.

### *3.3.3 Relations linking M5 for all durations (D) less than 2 days with 60 minute M5 and 2 day M5*

All the M5 data from the sets *a*, *b*, *c* and *d* of 3.3.1 were assembled. For durations less than 60 minutes, essentially all the variability could be accounted for by relating (*D* minute M5)/(60 minute M5) to AAR which in turn is closely associated with the ratio (60 minute M5)/(2 day M5), see

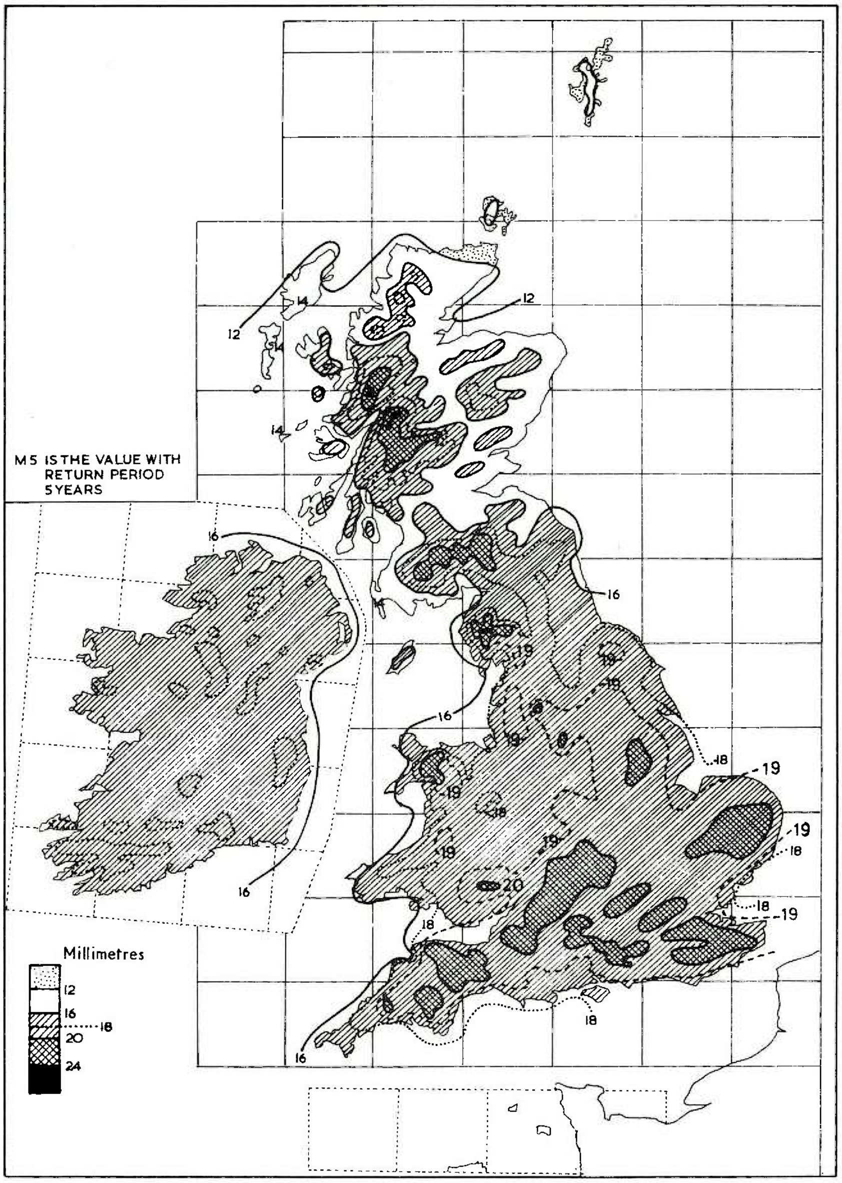



Fig. 3.6 A broad guide to 60 minute M5 rainfall (British Isles) (see text for method of obtaining accurate point value).

later. The relations are given in Table 3.6 (ratios for 120 minutes duration are also included).

Table 3.6 The $D$ minute M5 expressed as a percentage of the 60 minute M5 for various values of $r$ or AAR.

| $r$ | AAR (hundreds of mm) | $D$ 1 | 2 | 5 | 10 | 15 | 30 | 120 |
|---|---|---|---|---|---|---|---|---|
| 0.44 | 5–6 | 12 | 21 | 38 | 54 | 64 | 83 | 120 |
| 0.39 | 6–8 | 11 | 20 | 36 | 52 | 62 | 81 | 123 |
| 0.32 | 8–10 | 11 | 19 | 35 | 50 | 60 | 79 | 126 |
| 0.26 | 10–14 | 11 | 18 | 33 | 47 | 57 | 76 | 130 |
| 0.22 | 14–20 | 10 | 17 | 31 | 45 | 54 | 74 | 134 |
| 0.17 | 20–28 | 9 | 15 | 27 | 41 | 50 | 71 | 139 |
| 0.13 | 28–40 | 8 | 13 | 24 | 37 | 46 | 69 | 145 |
| 0.12 | 40– | 7 | 12 | 23 | 35 | 45 | 67 | 149 |

For durations between 60 minutes and 48 hours, the ratio (given duration M5)/(2 day M5) can be related with great exactitude to $r$, the mapped proportion (60 minute M5)/(2 day M5). In fact, there is very nearly a linear relation between (given duration M5)/(2 day M5) and $D$ on log log diagrams, with the ratio having the value of $r$ at $D = 60$ minutes, and 1.06 at $D = 48$ hours (Table 3.1). The relation between (given duration M5)/(2 day M5) and $r$ is given in Table 3.7.

**Table 3.7** Relation between percentage values of (given duration M5)/(2 day M5) and $r$, (60 minute M5)/(2 day M5).

| $r$ | $D$ | | | | | | |
|---|---|---|---|---|---|---|---|
| | 60 min | 120 min | 4 h | 6 h | 12 h | 24 h | 48 h |
| 0.12 | 12 | 18 | 26 | 33 | 49 | 72 | 106 |
| 0.15 | 15 | 21 | 30 | 37 | 53 | 75 | 106 |
| 0.18 | 18 | 25 | 34 | 41 | 56 | 77 | 106 |
| 0.21 | 21 | 28 | 38 | 45 | 60 | 80 | 106 |
| 0.24 | 24 | 32 | 41 | 48 | 63 | 81 | 106 |
| 0.27 | 27 | 35 | 44 | 51 | 65 | 83 | 106 |
| 0.30 | 30 | 38 | 48 | 54 | 68 | 85 | 106 |
| 0.33 | 33 | 41 | 51 | 57 | 70 | 86 | 106 |
| 0.36 | 36 | 44 | 54 | 60 | 73 | 88 | 106 |
| 0.39 | 39 | 47 | 57 | 63 | 75 | 89 | 106 |
| 0.42 | 42 | 50 | 60 | 66 | 77 | 90 | 106 |
| 0.45 | 45 | 53 | 63 | 68 | 79 | 92 | 106 |

The relations given in Table 3.6 and 3.7 are in good agreement with the model for M5 values for durations up to 2 days (Table 3.10)

$$I = \frac{I_0}{(1+BD)^n}$$

where

$I$ is the rainfall intensity = rainfall/duration,

$I_0$ is the instantaneous rainfall intensity (for very short durations, *viz.* 15 seconds),

$D$ is the duration in hours,

$n$ called a continentality factor, has low values in high rainfall areas with relatively light short duration falls and relatively heavy long duration falls; $n$ has high values in low rainfall areas with frequent thunderstorms, with relatively heavy short duration falls and light long duration falls,

$B$ increases with increasing AAR.

The values of instantaneous rainfall intensity from Jardi records showed that the M5 value for $I_0$ was of the order of 140 mm per hour in Scotland, and 150–175 mm per hour in England, Wales and Ireland. The parameters of the model also can be related approximately to AAR, as in Table 3.8.

**Table 3.8** Parameters of the M5 model $I = I_0/(1+BD)^n$ related approximately to AAR and $r$.

| AAR (hundreds of mm) | $I_0$ (mm/hour) | $n$ | $B$ | $r$ |
|---|---|---|---|---|
| 5–6 | 170 | 0.78 | 15 | 0.44 |
| 6–8 | 165 | 0.75 | 15 | 0.39 |
| 8–10 | 160 | 0.70 | 20 | 0.32 |
| 10–14 | 150 | 0.64 | 25 | 0.26 |
| 14–20 | 145 | 0.60 | 30 | 0.22 |
| 20–28 | 145 | 0.54 | 35 | 0.17 |
| 28–40 | 145 | 0.47 | 40 | 0.13 |
| 40– | 145 | 0.44 | 45 | 0.12 |

The model is relatively insensitive to variations in the parameters $B$, and to a lesser extent $I_0$. It was used to provide the values for the last two lines of Table 3.6. The model was not used to derive the values in Table 3.7; but since it is in excellent agreement with them, it was used for smoothing.

Table 3.7 has been used to give 1000 grid point estimates of 6 hour M5 to add to the 100 station estimates to prepare the large scale map available on request.

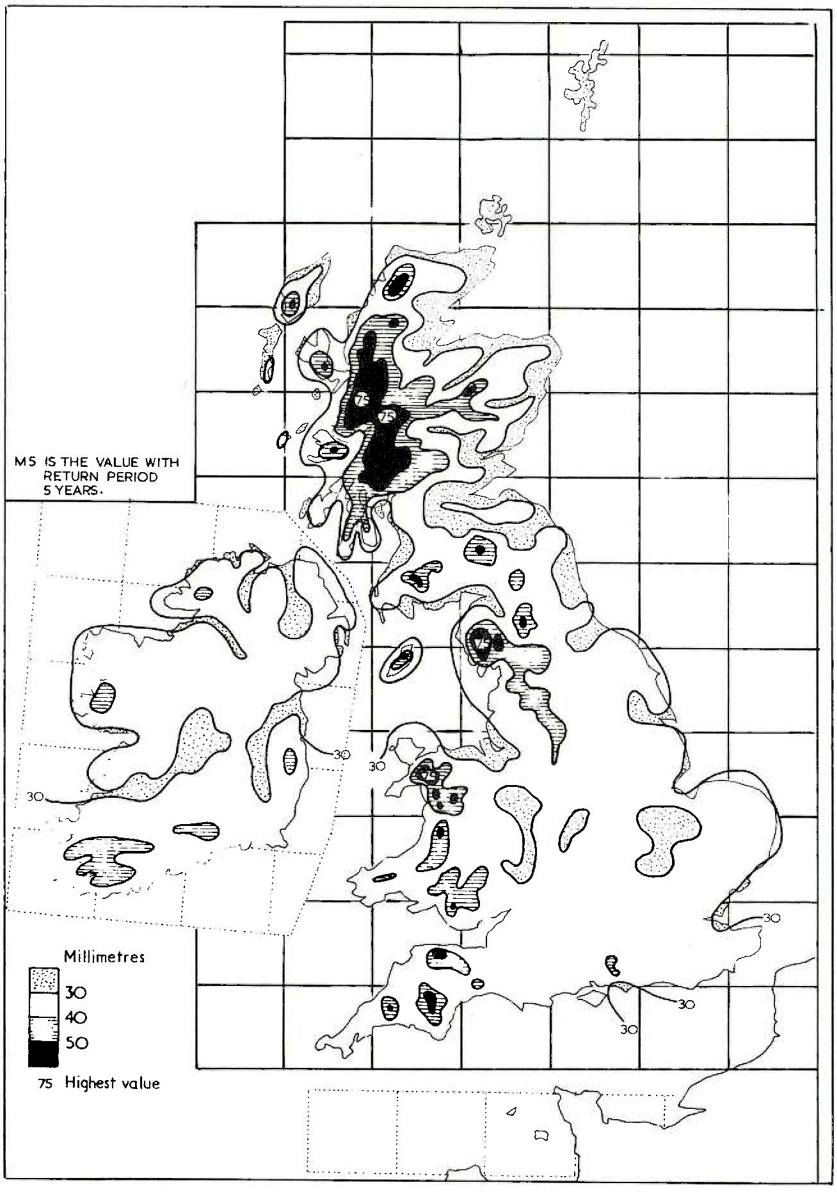



Fig. 3.7 A broad guide to 6 hour M5 rainfall (British Isles) (see text for method of obtaining accurate point value).

In view of the success of the model for M5 rainfall in representing M5 amounts for both durations less than 60 minutes (Table 3.6) and between 60 minutes and 48 hours (Table 3.7), it may be appropriate to present the results from the model for the whole range of durations, as a useful summary of both Tables 3.6 and 3.7, so that, given simply $r$, the ratio of 60 minute M5 to 2 day M5, a good estimate is given for M5 values for all durations from 1 minute to 48 hours as a percentage of 2 day M5. The results from the model are given in Section 3.6.

It should be emphasised that no theoretical basis is claimed for the model, and the model has not been used to do more than smooth results already obtained from the data.

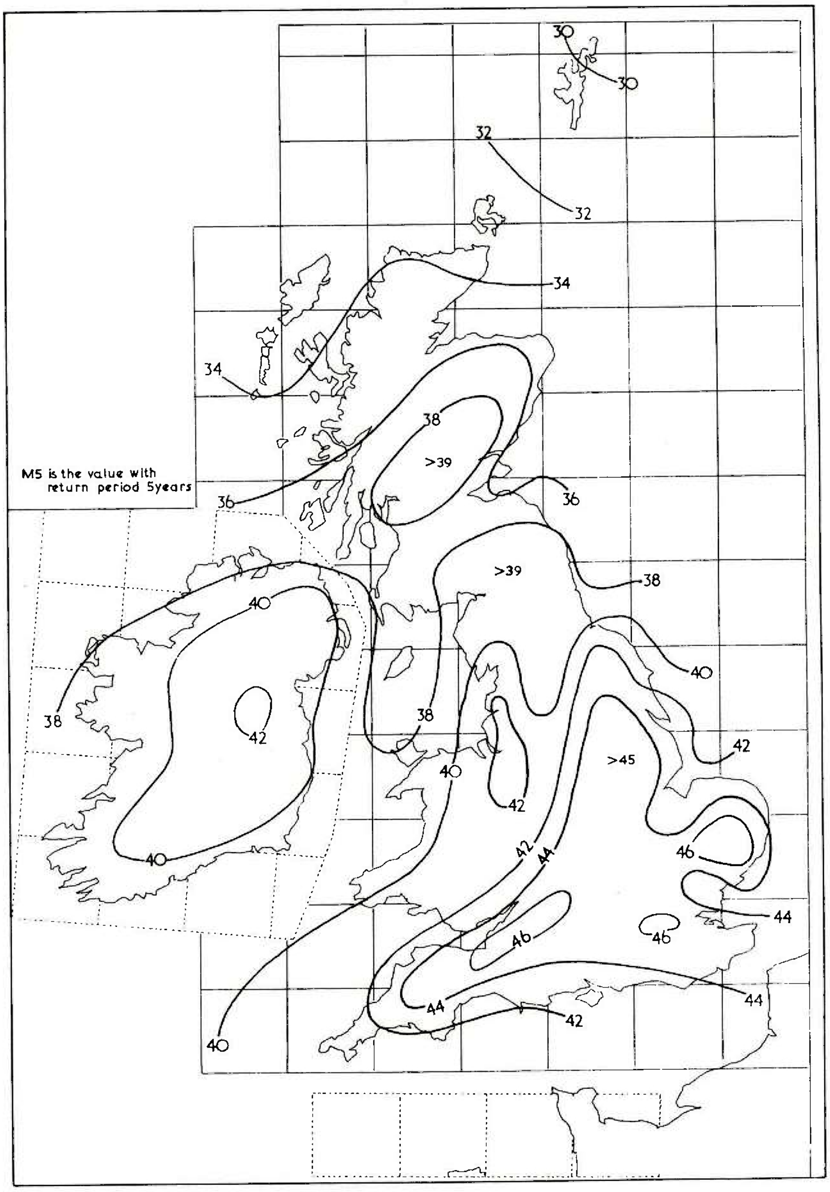



Fig 3.8 M5 precipitable water (mm) (British Isles) corresponding to a saturated column of air whose base temperature is the M5 value of dew point persisting for at least 6 hours.

### 3.4 Values of M5 for monthly and seasonal maxima for various durations

The estimates of M5 for monthly and seasonal maxima for the short duration data of 3.3.1, and the long duration data (1 day to 25 day), were assembled. Values of M5 for maxima for each individual month, and for each season, were expressed as percentages of the corresponding value of M5 for annual maxima. The seasons were taken as, winter from November to April, and summer from May to October. This is the most appropriate division of the year into two seasons according to amount of precipitable water *w*; but of course any subdivision is unlikely to be in accord with every meteorological element.

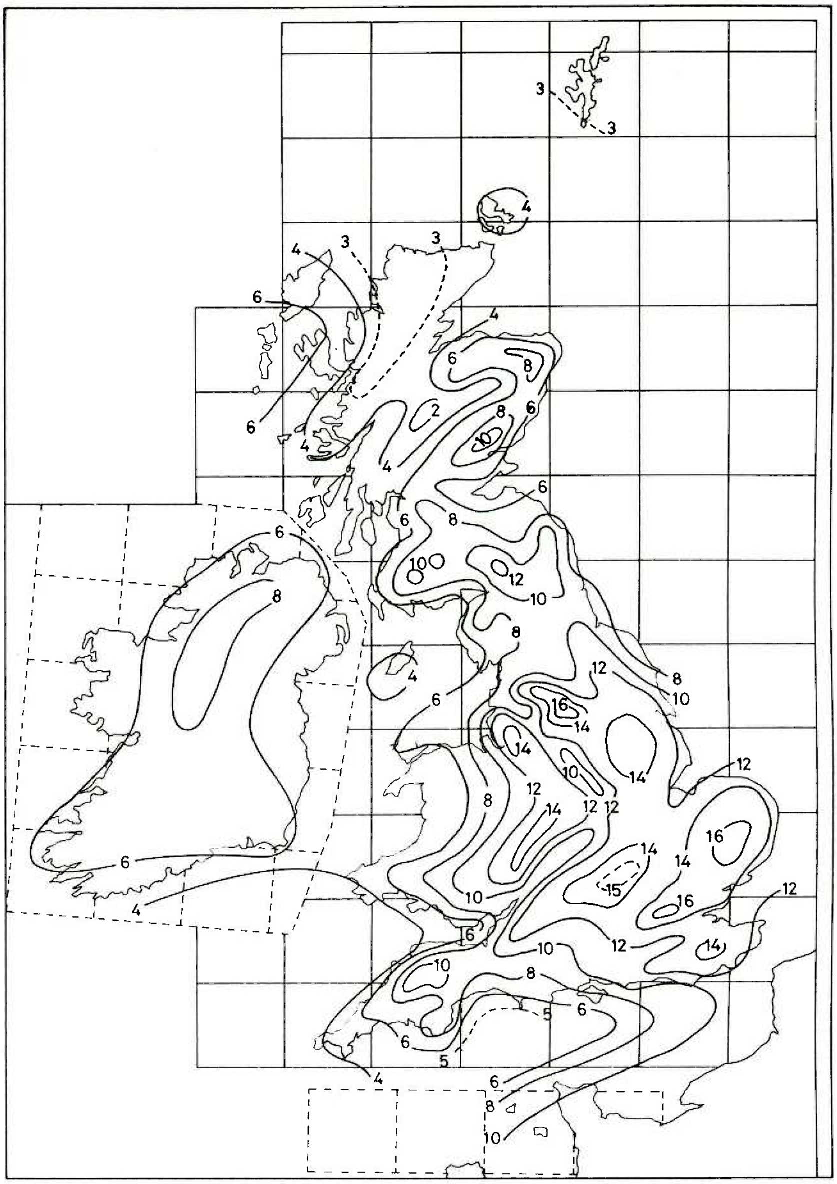


Fig 3.9 Average number of days per year with thunder (simplified map, British Isles).

The variation of the percentages for monthly and seasonal maxima is given in Table 3.9, for durations 1, 2, 6 hours, 1, 2, 4, 8, 25 days; and for AAR bands (hundreds of mm) 5–6, 6–8, 8–10, 10–14, 14–20, >20, since the variability from region to region was found to be essentially accounted for by variations in AAR.

### 3.5 Rainfall cycles

Irregular or quasiregular fluctuations of rainfall with periods less than 50 years might be of some practical significance if the range of the rainfall fluctuations were sufficiently large. But only the short period (12 years or less) quasiregular fluctuations (cycles) appear to be large enough to be of much practical importance. An example of rainfall cycles is given below.

For each of 22 stations in eastern England the 20 annual maximum falls (1951–70) were recorded as percentages of the M2 fall. Then, for each year,

**Table 3.9** Variation of M5, for monthly and seasonal maxima (expressed as % of M5 for annual maxima), with duration and AAR (mm).

| Duration | Jan. | Feb. | Mar. | April | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. | Summer | Winter |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AAR 500–600 | | | | | | | | | | | | | | |
| 1 h | 27 | 24 | 25 | 28 | 43 | 57 | 69 | 66 | 52 | 43 | 36 | 30 | 100 | 43 |
| 2 h | 30 | 26 | 29 | 32 | 47 | 61 | 71 | 71 | 57 | 46 | 40 | 33 | 100 | 48 |
| 6 h | 33 | 29 | 31 | 33 | 45 | 58 | 66 | 68 | 53 | 47 | 46 | 38 | 99 | 55 |
| 1 day | 40 | 34 | 37 | 36 | 46 | 51 | 64 | 62 | 54 | 52 | 49 | 41 | 97 | 65 |
| 2 day | 43 | 38 | 40 | 40 | 47 | 51 | 64 | 63 | 55 | 54 | 55 | 45 | 96 | 71 |
| 4 day | 45 | 40 | 42 | 41 | 48 | 52 | 65 | 59 | 56 | 57 | 57 | 49 | 96 | 73 |
| 8 day | 47 | 41 | 43 | 41 | 48 | 52 | 63 | 61 | 54 | 60 | 60 | 51 | 95 | 74 |
| 25 day | 51 | 44 | 45 | 48 | 52 | 50 | 69 | 66 | 60 | 59 | 58 | 54 | 93 | 78 |
| AAR 600–800 | | | | | | | | | | | | | | |
| 1 h | 31 | 26 | 27 | 30 | 42 | 54 | 66 | 65 | 52 | 45 | 39 | 33 | 100 | 47 |
| 2 h | 35 | 30 | 30 | 32 | 45 | 56 | 66 | 68 | 56 | 50 | 45 | 37 | 99 | 52 |
| 6 h | 41 | 35 | 36 | 38 | 48 | 57 | 66 | 71 | 57 | 51 | 53 | 44 | 99 | 61 |
| 1 day | 45 | 39 | 39 | 38 | 48 | 50 | 63 | 65 | 56 | 56 | 53 | 46 | 96 | 70 |
| 2 day | 48 | 42 | 42 | 41 | 48 | 50 | 63 | 65 | 57 | 59 | 57 | 50 | 95 | 74 |
| 4 day | 51 | 45 | 44 | 43 | 49 | 50 | 63 | 65 | 57 | 62 | 61 | 55 | 95 | 79 |
| 8 day | 54 | 46 | 44 | 42 | 49 | 50 | 62 | 65 | 56 | 64 | 64 | 58 | 93 | 81 |
| 25 day | 56 | 46 | 45 | 47 | 47 | 50 | 64 | 64 | 55 | 61 | 68 | 60 | 88 | 86 |
| AAR 800–1000 | | | | | | | | | | | | | | |
| 1 h | 39 | 33 | 32 | 33 | 43 | 52 | 65 | 68 | 60 | 55 | 48 | 42 | 98 | 57 |
| 2 h | 43 | 36 | 35 | 35 | 44 | 53 | 64 | 69 | 63 | 57 | 52 | 45 | 98 | 60 |
| 6 h | 47 | 40 | 39 | 40 | 46 | 54 | 64 | 72 | 61 | 59 | 58 | 50 | 97 | 68 |
| 1 day | 51 | 44 | 42 | 40 | 47 | 49 | 61 | 64 | 58 | 62 | 58 | 54 | 94 | 76 |
| 2 day | 54 | 48 | 45 | 42 | 48 | 49 | 61 | 63 | 59 | 64 | 62 | 58 | 93 | 81 |
| 4 day | 57 | 50 | 46 | 44 | 48 | 49 | 60 | 63 | 59 | 67 | 66 | 61 | 92 | 83 |
| 8 day | 59 | 51 | 47 | 43 | 47 | 48 | 57 | 62 | 57 | 68 | 69 | 64 | 90 | 86 |
| 25 day | 68 | 57 | 46 | 46 | 46 | 50 | 57 | 61 | 57 | 64 | 71 | 65 | 88 | 91 |
| AAR 1000–1400 | | | | | | | | | | | | | | |
| 1 h | 45 | 44 | 42 | 37 | 46 | 55 | 62 | 68 | 69 | 61 | 54 | 51 | 96 | 70 |
| 2 h | 50 | 48 | 45 | 40 | 47 | 59 | 64 | 67 | 71 | 62 | 57 | 53 | 95 | 74 |
| 6 h | 57 | 54 | 49 | 44 | 50 | 54 | 63 | 64 | 69 | 66 | 61 | 60 | 91 | 79 |
| 1 day | 57 | 50 | 46 | 44 | 47 | 51 | 61 | 64 | 63 | 66 | 64 | 59 | 92 | 83 |
| 2 day | 60 | 52 | 48 | 45 | 48 | 51 | 60 | 63 | 63 | 69 | 67 | 62 | 91 | 85 |
| 4 day | 63 | 55 | 49 | 46 | 49 | 51 | 60 | 63 | 65 | 73 | 71 | 67 | 91 | 88 |
| 8 day | 66 | 56 | 48 | 45 | 47 | 49 | 57 | 63 | 64 | 73 | 73 | 69 | 89 | 90 |
| 25 day | 69 | 59 | 46 | 46 | 46 | 50 | 57 | 60 | 62 | 68 | 74 | 70 | 86 | 92 |
| AAR 1400–2000 | | | | | | | | | | | | | | |
| 1 h | 53 | 55 | 50 | 42 | 50 | 57 | 63 | 67 | 66 | 60 | 59 | 57 | 93 | 77 |
| 2 h | 59 | 60 | 55 | 45 | 52 | 58 | 65 | 68 | 70 | 63 | 63 | 62 | 92 | 84 |
| 6 h | 61 | 61 | 55 | 45 | 46 | 47 | 55 | 58 | 65 | 65 | 63 | 65 | 89 | 87 |
| 1 day | 65 | 56 | 48 | 46 | 45 | 48 | 54 | 58 | 61 | 69 | 67 | 65 | 86 | 89 |
| 2 day | 68 | 58 | 49 | 47 | 45 | 47 | 54 | 56 | 62 | 71 | 70 | 67 | 85 | 91 |
| 4 day | 71 | 61 | 51 | 48 | 46 | 47 | 53 | 57 | 63 | 74 | 73 | 71 | 86 | 93 |
| 8 day | 72 | 61 | 48 | 45 | 43 | 44 | 50 | 55 | 61 | 74 | 73 | 71 | 84 | 94 |
| 25 day | 73 | 61 | 46 | 38 | 38 | 40 | 49 | 58 | 63 | 73 | 76 | 79 | 83 | 94 |
| AAR > 2000 | | | | | | | | | | | | | | |
| 1 h | 58 | 60 | 58 | 51 | 56 | 61 | 67 | 73 | 76 | 69 | 64 | 64 | 94 | 83 |
| 2 h | 63 | 63 | 62 | 53 | 56 | 59 | 63 | 66 | 74 | 70 | 68 | 68 | 93 | 88 |
| 6 h | 65 | 65 | 61 | 51 | 54 | 55 | 62 | 64 | 70 | 68 | 65 | 68 | 90 | 90 |
| 1 day | 64 | 56 | 50 | 47 | 43 | 47 | 52 | 56 | 60 | 64 | 67 | 65 | 84 | 90 |
| 2 day | 67 | 58 | 51 | 47 | 43 | 47 | 52 | 55 | 61 | 66 | 70 | 67 | 82 | 93 |
| 4 day | 70 | 61 | 53 | 47 | 43 | 47 | 51 | 55 | 62 | 70 | 72 | 70 | 83 | 93 |
| 8 day | 71 | 61 | 50 | 45 | 42 | 44 | 49 | 54 | 60 | 71 | 71 | 70 | 82 | 94 |
| 25 day | 71 | 57 | 49 | 40 | 36 | 35 | 44 | 51 | 55 | 64 | 72 | 76 | 76 | 95 |

the median value of 2 hour falls for the 22 stations was evaluated and the resultant fluctuations are shown in Figure 3.10.

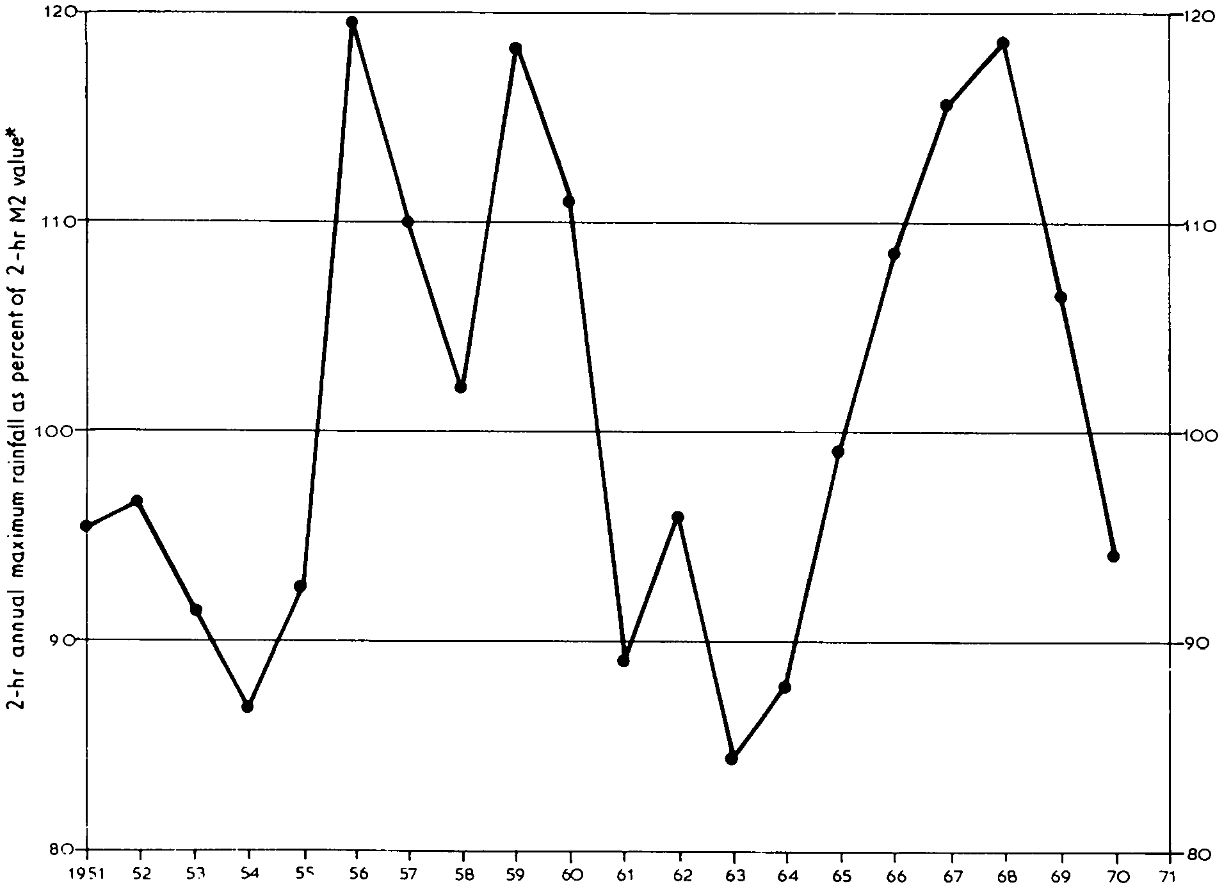



**Fig 3.10** Variation of 2 hour annual maximum rainfall (median value of 22 stations). * M2 is the value with return period 2 years.

### 3.6 Appendix: *model for 5 year rainfall intensities*

The model for rainfall intensities with return period 5 years is

$$I = \frac{I_0}{(1+BD)^n}$$

where $I$ is rainfall intensity, $I_0$ instantaneous intensity (mm per hour when 2 day M5 is in mm), $n$ is a continentality parameter, $B$ varies with AAR, and $D$ is duration in hours.

Due to the close association of $r$ with AAR, values of $B$ are associated with given values of $r$. Then for a given 60 minute rainfall, expressed as $r\%$ of 2 day M5, there is an associated value of $B$. The 48 hour rainfall is 106% of 2 day M5. From these, the 'continentality' factor $n$ follows. So, given $r$, which has its associated value of $B$, M5 rainfall values can be computed from the model, including $I_0$, all as percentages of 2 day M5. The following table (Table 3.10) gives the associated values $r$ and $B$, and then tabulates $n$ and $I_0$, with rainfall for durations from 1 minute to 48 hours.

**Table 3.10** Model for M5 rainfall for durations up to 48 hours.

| | | | Percent of 2 day M5 | M5 rainfall (amounts as percentages of 2 day M5) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $r$ | $B$ | $n$ | $I_0$ | 1 min | 2 min | 5 min | 10 min | 15 min | 30 min | 60 min | 2 h | 4 h | 6 h | 12 h | 24 h | 48 h |
| 12 | 45 | 0.440 | 65 | 0.8 | 1.4 | 2.7 | 4.2 | 5.4 | 8.1 | 12 | 18 | 26 | 33 | 49 | 72 | 106 |
| 15 | 39 | 0.498 | 94 | 1.2 | 2.1 | 3.8 | 5.8 | 7.2 | 10.5 | 15 | 21 | 30 | 37 | 53 | 75 | 106 |
| 18 | 34 | 0.546 | 125 | 1.6 | 2.8 | 5.0 | 7.4 | 9.2 | 12.9 | 18 | 25 | 34 | 41 | 56 | 77 | 106 |
| 21 | 30 | 0.587 | 157 | 2.1 | 3.5 | 6.3 | 9.2 | 11.2 | 15.5 | 21 | 28 | 38 | 45 | 60 | 80 | 106 |
| 24 | 27 | 0.622 | 191 | 2.5 | 4.3 | 7.6 | 11.0 | 13.3 | 18.1 | 24 | 31 | 41 | 48 | 63 | 81 | 106 |
| 27 | 24 | 0.653 | 221 | 3.0 | 5.0 | 9.0 | 12.9 | 15.5 | 20.7 | 27 | 35 | 44 | 51 | 65 | 83 | 106 |
| 30 | 21 | 0.682 | 247 | 3.3 | 5.7 | 10.3 | 14.8 | 17.7 | 23.3 | 30 | 38 | 48 | 55 | 68 | 85 | 106 |
| 33 | 19 | 0.708 | 275 | 3.8 | 6.5 | 11.7 | 16.7 | 19.9 | 26.0 | 33 | 41 | 51 | 57 | 71 | 87 | 106 |
| 36 | 17 | 0.732 | 298 | 4.1 | 7.2 | 13.0 | 18.6 | 22.2 | 28.7 | 36 | 44 | 54 | 60 | 73 | 88 | 106 |
| 39 | 16 | 0.753 | 329 | 4.6 | 8.0 | 14.5 | 20.6 | 24.5 | 31.5 | 39 | 47 | 57 | 63 | 75 | 89 | 106 |
| 42 | 15 | 0.773 | 359 | 5.0 | 8.7 | 16.0 | 22.7 | 26.9 | 34.2 | 42 | 50 | 60 | 66 | 77 | 91 | 106 |
| 45 | 14 | 0.792 | 385 | 5.4 | 9.5 | 17.4 | 24.7 | 29.2 | 37.0 | 45 | 53 | 63 | 68 | 79 | 92 | 106 |

## 3.7 Suggestions for further reading

BILHAM E. G. (1935) Classification of heavy falls in short periods *British Rainfall*, 262–280. HMSO.

GLASSPOOLE J. (1931) Heavy falls in short periods (two hours or less). *Quarterly Journal of the Royal Meteorological Society*, **58**, 57–70.

HERSCHFIELD D. & WILSON W. T. (1957) Generalising of rainfall-intensity-frequency data. *Proceedings of the International Association of Scientific Hydrology, General Assembly of Toronto*, **1**, 499–506.

PARTHASARATHY K. & GURBACHAN SINGH (1961) Rainfall intensity-duration-frequencies for India, for local drainage design. *The Indian Journal of Meteorology and Geophysics*, **12**, 231–242.

# 4 Estimated maximum falls of rain

## 4.1 Summary

The storm efficiency, that is, the ratio of rainfall to amount of precipitable water in the representative air column during the storm, was calculated for major 24 hour and 2 hour United Kingdom storms. The maximum observed values for the United Kingdom were, for 24 hour storms, 9.3 for summer storms and 12.2 for winter storms. The maximum was 3.86 for summer 2 hour storms. All storms were then re-examined, and the rainfalls adjusted to the appropriate maximum storm efficiency. The 2 hour falls were correlated with the M5 value of precipitable water and estimated maximum 2 hour rainfall thus mapped (Figure 4.1, included in Volume V).

There was broad agreement between the estimated maxima for different regions for 24 hours and the corresponding estimated maxima from a consideration of the envelope of the growth curves in Figure 2.3. A map of estimated 24 hour maximum rainfall, utilising the 2 day M5 values, was prepared (Figure 4.2, Volume V). Tables 4.1 and 4.3 were similarly prepared to allow rainfall to be estimated for durations less than 2 hours and for durations greater than 24 hours respectively.

## 4.2 Estimated maximum 2 hour rainfall

For 60 stations, the maximum dew point persisting for at least 6 hours was recorded for each month of record. From these records, maps of M5 dew point were prepared, and monthly and seasonal variations noted.

The amounts of precipitable water, corresponding to a saturated column of air whose base temperature is the M5 value of dew point, were calculated and mapped (Figure 3.8). The values corresponding to observed maximum dew points show the same pattern, with amounts some 20–25% greater.

It would be reasonable to expect that values of maximum short duration falls of rain, e.g. for 2 hours, would follow the same pattern, with much the same proportionality factor for the United Kingdom, since it would be expected that convective mechanisms for the maximum storms would produce the same vertical profile of divergence and hence the same maximum storm efficiency.

For major 2 hour storms (including mountain storms), the highest values of storm efficiency were:

| Storm efficiency | Date | Place | Estimated rainfall (mm) | Estimated dewpoint (°C) |
|---|---|---|---|---|
| 3.04 | 29 May 1920 | Louth, Lincs. | 104 | 14½ |
| 3.20 | 10 Aug. 1957 | Llansadwrn, Anglesey | 125 | 16 |
| 3.27 | 1 Aug. 1972 | Costessey, Norfolk | 117 | 15 |
| 3.50† | 11 June 1956 | Hewenden, Yorks. | 102 | 12 |
| 3.72 | 18 Aug. 1924 | Cannington, Somerset | 127 | 15 |
| 3.78 | 8 June 1957 | Camelford, Cornwall | 125 | 14 |
| 3.86 | 7 Oct. 1960 | Horncastle, Lincs. | 117 | 13 |

†The original value was 5.30, obtained from the report of 155 mm of rain in 2 hours, but this very intense rainfall with a dew point of only 12°C is not acceptable on the scientific evidence available from investigations of storms.

Values approaching the maximum, 3.86, were observed in all the major regions of the United Kingdom; and this value was taken as the probable maximum in any region. For each major 2 hour storm, the amount of rainfall was computed that would have fallen if this maximum storm efficiency had been reached on that occasion. The greatest maximised falls (mm) for each region were: eastern England 208, 185, 185, 185; south west England 185, 170; west England and Wales 183, 165; Scotland and Northern Ireland 150, 137. The value of 208 mm for eastern England was regarded as somewhat high when compared with the values in Chapter 9.

These falls were correlated with M5 precipitable water content, and estimated maximum 2 hour rainfall mapped (Figure 4.1).

The estimated maximum 2 hour falls are generally supported by the maximum estimated by considering the envelope of the growth curves (Figures 2.3 and 2.4). Unfortunately, the envelope of the growth curves is not clearly defined for durations of less than about 6 hours, and the results thus obtained for 2 hour falls are considered less satisfactory than those presented in Figure 4.1. The estimated maximum growth factors given in Figure 2.4 were, however, used to determine the maximum rainfall as a percentage of the 2 hour maximum, for durations less than 2 hours (see 4.2.2).

### *4.2.1 Frequency of occurrence of heavy 2 hour falls in south east England*

At a given representative point in the south east of England with AAR less than 750 mm, the M5 2 hour rainfall is about 25 mm, the 100 year value 50–55 mm, the 1000 year value 85–90 mm, the 10 000 year value 140–150 mm, and the estimated maximum 190–200 mm. But it should be noted that, although a fall of 90 mm in 2 hours is an extremely rare event at any given place, such a fall is reported once every 10 years or so. Examples of such falls are given in Chapter 9.

The '10 year' events for the region are 35 mm for 15 minutes, 50 mm for 30 minutes, 70 mm for 60 minutes, and 90 mm for 2 hours.

The '50 year' events for the region are 45 mm for 15 minutes, 65 mm for 30 minutes, 90 mm for 60 minutes and 120 mm for 2 hours. These values should be increased by 25% to allow for '50 year' events for the United Kingdom as a whole.

### *4.2.2 Estimated maximum falls for duration less than 2 hours*

By taking the parameters of the model for M5 values given in Table 3.8 and using the envelope of the growth factors in Figure 2.4, we find, as might be expected, that for maximum rainfalls the proportions (given duration $MT$)/(120 minute $MT$) vary much less with AAR than the M5 proportions given in Table 3.6; and mean values may be taken as given in Table 4.1.

**Table 4.1** Maximum falls in short durations as percentage of estimated 2 hour maximum fall, related to AAR

| AAR (hundreds of mm) | Duration (minutes) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 5 | 10 | 15 | 30 | 60 |
| 5–14 | 6 | 11 | 23 | 36 | 47 | 65 | 83 |
| 14–28 | 6 | 11 | 22 | 34 | 45 | 62 | 79 |
| 28– | 6 | 10 | 21 | 32 | 43 | 59 | 75 |

## 4.3 Estimated maximum 24 hour rainfall

### *4.3.1 Maximised storm rainfalls*

The three highest values of storm efficiency in summer 24 hour storms were 9.3, 8.7, 8.6. The value of 9.3 for the 24 hour storm at Cannington (Somerset) on the 18/19 August 1924, was taken as the probable maximum in any region. The three highest values of storm efficiency in winter 24 hour storms were 12.2, 11.5, 11.5. The value of 12.2 for the 24 hour storm at Loch Quoich (Cruadhach) on the 17/18 December 1954 was taken as the probable maximum. When these probable maximum values of storm efficiency, for summer and winter storms respectively, were applied to ail major storms, the greatest maximised falls were as follows:

*a* Areas with annual maximum 24 hour falls occurring in summer—eastern England 270 mm; south west England 410 mm, 330 mm; Scottish Lowlands 245 mm, 225 mm.

*b* Areas with annual maximum 24 hour fall occurring in winter—the mountainous areas of the west 378 mm, 320 mm.

NB Maximised summer falls for these areas were 310 mm, 300 mm.

### *4.3.2 An initial quick estimate of maximum rainfall from the growth curves*

An initial quick estimate of the maximum rainfall, for any duration, anywhere in the United Kingdom can be obtained from a knowledge of the M5 value, by utilising the envelope of the growth factors in Figure 2.4. A line, which is an envelope of all known maximum values, is shown on the right hand side of Figure 2.3. The estimated maxima are given in Table 4.2 for England and Wales and separately for Scotland and Northern Ireland.

**Table 4.2** Initial quick estimates of maximum rainfall (mm) from a knowledge of M5 alone.

| M5 (mm) | 2 | 5 | 10 | 15 | 20 | 25 | 30 | 40 | 50 | 75 | 100 | 150 | 200 | 500 | 1000 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| England and Wales | 10 | 27 | 66 | 111 | 156 | 189 | 215 | 253 | 280 | 297 | 326 | 388 | 460 | 812 | 1420 |
| Scotland and Northern Ireland | 10 | 30 | 71 | 109 | 135 | 158 | 178 | 212 | 241 | 280 | 326 | 388 | 460 | 812 | 1420 |

Example: A place in England or Wales with a 2 day M5 equal to 50 mm, can expect a maximum 2 day rainfall of approximately 280 mm.

By considering the envelope of the growth factors in Figure 2.4, together with M5 values given in Table 3.4, it was possible to obtain initial approximate values for estimates of the expected maximum falls, for durations 1-25 days, given AAR alone. These are given in Table 4.3.

**Table 4.3** Scheme for obtaining initial approximate values for estimated maximum rainfall for durations 1-25 days, from a knowledge of AAR alone.

| AAR (hundreds of mm) | Approx. 2 day M5 (mm) | Approximate values of estimated maximum falls (mm) for durations | | | | | |
|---|---|---|---|---|---|---|---|
| | | 24 h | 48 h | 72 h | 96 h | 192 h | 25 days |
| 5–6 | 44 | 231 | 254 | 262 | 270 | 287 | 343 |
| 6–8 | 50 | 246 | 267 | 276 | 283 | 301 | 379 |
| 8–10 | 59 | 261 | 278 | 287 | 293 | 333 | 439 |
| 10–14 | 71 | 275 | 290 | 302 | 320 | 369 | 529 |
| 14–20 | 92 | 289 | 323 | 343 | 358 | 430 | 646 |
| 20–28 | 124 | 323 | 365 | 390 | 421 | 521 | 805 |
| 28–40 | 177 | 369 | 442 | 484 | 526 | 661 | 1066 |
| 40– | 211 | 400 | 491 | 542 | 594 | 750 | 1238 |

### 4.3.3 Estimated maximum 24 hour and longer duration rainfall

The good agreement of the rough 24 hour estimates in Table 4.3 with the maximised values from the major storms gave encouragement to make detailed estimates from the 2 day M5 map. These were then used in conjunction with the storm maximised values to map out the estimated 24 hour maximum falls over the United Kingdom. They are shown in Figure 4.2 and may be compared with examples in Chapter 9.

The most notable areas of maxima are: 350–400 mm for summer storms over Exmoor (winter storms may also give 300 mm); and 350–375 mm for winter storms over the Scottish Highlands, Snowdonia, the Lake District, and Dartmoor. (Summer storms in these areas may give 300–325 mm.) In most lowland areas the maxima, which occur in summer, are likely to be 250–275 mm (winter storms may give 175–200 mm in these areas).

Although the estimated maxima in Table 4.3 should only be used as a general guide, the (smoothed) within duration ratios in Table 4.3 may be used to apply to the 24 hour maxima of Figure 4.2 to obtain estimates of 48, 72, 96 hour maxima. Table 4.4 gives the within duration ratios for 48, 72, 96, 192 hour and 25 day values to the value for 24 hours; and also the ratio 192 hour to 25 day value.

**Table 4.4** Within duration ratios for estimated maxima, related to AAR.

| AAR (hundreds of mm) | Ratios of estimated maxima to those for 24 h | | | | | Ratio of maximum 192 h to that for 25 days |
|---|---|---|---|---|---|---|
| | 48 h | 72 h | 96 h | 192 h | 25 days | |
| 5–6 | 1.10 | 1.13 | 1.17 | 1.24 | 1.48 | 0.84 |
| 6–8 | 1.10 | 1.13 | 1.17 | 1.25 | 1.54 | 0.80 |
| 8–10 | 1.10 | 1.14 | 1.18 | 1.28 | 1.68 | 0.76 |
| 10–14 | 1.11 | 1.16 | 1.20 | 1.35 | 1.92 | 0.71 |
| 14–20 | 1.12 | 1.18 | 1.24 | 1.49 | 2.20 | 0.68 |
| 20–28 | 1.14 | 1.23 | 1.32 | 1.62 | 2.49 | 0.65 |
| 28–40 | 1.20 | 1.31 | 1.42 | 1.79 | 2.89 | 0.62 |
| 40 | 1.23 | 1.35 | 1.48 | 1.87 | 3.09 | 0.60 |

It is, however, preferable for 25 days to estimate the 25 day M5 from Figure 3.4 and the AAR (Figure 3.1), and then to use Table 4.2 to obtain an estimate of the maximum. The ratio of maximum 192 hour to 25 day rainfall from Table 4.4 should then be used to obtain a value for the 192 hour maximum. This should be preferred to that obtained from the ratio 192 hour to 24 hour maximum.

The estimates for the different durations should be plotted against the logarithm of the duration and smoothed.

### 4.3.4 Estimated maximum rainfalls for durations 2–24 hours

Estimates of maximum rainfall for durations between 2 and 24 hours may be obtained from a straight line relation between rainfall and the logarithm of duration in hours, using the maximum falls for 2 hours and 24 hours from Figures 4.1 and 4.2 to give the line.

### 4.4 Suggestions for further reading

BLEASDALE A. (1963) The distribution of exceptionally heavy falls of rain in the United Kingdom, 1863–1960. *Journal of the Institution of Water Engineers*, **17**, 45–55.

GLASSPOOLE J. (1930) The areas covered by intense and widespread falls of rain. *Proceedings of the Institution of Civil Engineers*, **229**, session 1929–30, Part 1.

MYERS V.A. (1969) *Estimation of Maximum Floods*, Chap. 2. Technical Note No. 98, World Meteorological Organisation, Geneva.

# 5 Areal rainfall

## 5.1 Summary

The factor which, when applied to point rainfall for specified duration and return period, gives the areal rainfall for the same duration and return period, may be termed the 'areal reduction factor' for the given area. The areal reduction factor, ARF, for a given area and specified duration, does not vary much with return period and it is assumed that in a given region ARF varies only with the size of the area and the specified duration. The variation with duration and size of area was the same for a wide variety of regions of the United Kingdom, and these variations of ARF for durations from 1 minute to 25 days and for area sizes from 1 km² to 30 000 km² have been analysed and are summarised in Table 5.2 and in Figure 5.1.

## 5.2 The areal reduction factor, ARF

Chapters 2–4 have discussed the estimation of rainfall at a point for a given duration and a given return period. As most practical problems are concerned with the volume of rain falling on an area, it is necessary to be able to estimate, for a specified area, the areal mean rainfall for a given duration and a given return period. This will of course be less than the corresponding point rainfall, and the areal fall may be expressed simply as a proportion of the representative point rainfall. This proportion may be termed the 'areal reduction factor', ARF. In a given catchment, for specified area $A$ and return period $T$, ARF will obviously increase with increasing duration $D$; for specified $D$ and $T$, ARF will obviously decrease with increasing area $A$; for specified $A$ and $D$, it is not clear how ARF will vary with return period $T$, but experience shows that this variation is only slight, and may be ignored for practical purposes. That is, for specified $A$ and $D$, areal and point rainfall have the same ratio for say 2 year and 100 year events. If we specify the variations of ARF with varying $A$ and $D$ in a given region, this enables us to estimate areal rainfall from point rainfall. Investigations for widely different regions of the United Kingdom showed that the variation of ARF with $A$ and $D$ is the same everywhere. The experimental values for ARF are given in Table 5.1.

*a* In the Cardington and Winchcombe areas with $A = 10$ km²

| | D(min) | | | | |
|---|---|---|---|---|---|
| | 2 | 4 | 10 | 30 | 60 |
| ARF | 0.67 | 0.74 | 0.85 | 0.88 | 0.90 |

*b* An area of 100 km² in Surrey

| | D | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 15 min | 30 min | 60 min | 2 h | 1 day | 2 days | 4 days | 8 days | 25 days |
| ARF | 0.62 | 0.73 | 0.77 | 0.84 | 0.94 | 0.97 | 0.97 | 0.97 | 0.99 |

*c* An area of 1000 km² in Surrey

| | D | | | |
|---|---|---|---|---|
| | 15 min | 30 min | 60 min | 2 h |
| ARF | 0.39 | 0.51 | 0.62 | 0.75 |

*d* Meaned values from four areas of 1500 km², three in the Trent catchment and one centred on the Chilterns

| | *D* | | | | |
|---|---|---|---|---|---|
| | 1 day | 2 days | 4 days | 8 days | 25 days |
| ARF | 0.89 | 0.91 | 0.92 | 0.93 | 0.97 |

*e* Meaned values from two areas of 5000 km², each in the south west of England

| | *D* | | | | |
|---|---|---|---|---|---|
| | 1 day | 2 days | 4 days | 8 days | 25 days |
| ARF | 0.84 | 0.85 | 0.88 | 0.89 | 0.94 |

*f* An area of 8000 km² centred on the Chilterns

| | *D* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 h | 2 h | 3 h | 6 h | 1 day | 2 days | 4 days | 8 days | 25 days |
| ARF | 0.47 | 0.57 | 0.64 | 0.74 | 0.83 | 0.85 | 0.87 | 0.91 | 0.95 |

*g* An area of 10 000 km² in south west England

| | *D* | | | | |
|---|---|---|---|---|---|
| | 1 day | 2 days | 4 days | 8 days | 25 days |
| ARF | 0.82 | 0.83 | 0.87 | 0.89 | 0.94 |

*h* An area of 18 000 km² centred on the Chilterns

| | *D* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 h | 2 h | 3 h | 6 h | 1 day | 2 days | 4 days | 8 days | 25 days |
| ARF | 0.40 | 0.51 | 0.57 | 0.67 | 0.81 | 0.83 | 0.84 | 0.87 | 0.93 |

**Table 5.1** Values of ARF.

Since ARF does not vary appreciably with return period, the following simple objective method was adopted to give an estimate for return period 2–3 years.

In a given catchment, for a specified area *A* and duration *D*, the maximum areal event for each year was noted, after lists of notable events had been tabulated. For the maximum areal event the station rainfalls R1 were noted at each station in the area. These will also be identical with the station annual maxima R2 (for duration *D*) for a number of stations. The ratios R1/R2 were noted, and mapped for each year; and an areal mean value of R1/R2 obtained, as the mean over a large number of interpolated grid points if necessary. Then the mean over a number of years of these areal means is the value of ARF for the given *A* and *D*. The method is very transparent, indicating very clearly the degree of areal coherence for a given area and duration, and showing how this may vary from year to year.

From the data of Table 5.1, smoothed values of ARF for ranges of values of *D* from 1 minute to 25 days, and of *A* from 1 km$^2$ to 30 000 km$^2$ were obtained. These are given in Table 5.2. To simplify interpolation for any *A* and *D* combination, ARF may be displayed as isopleths on a log *A*, log *D* diagram, as in Figure 5.1.

Fig. 5.1 Areal reduction factor (ARF), %, related to area $A$ and duration $D$.

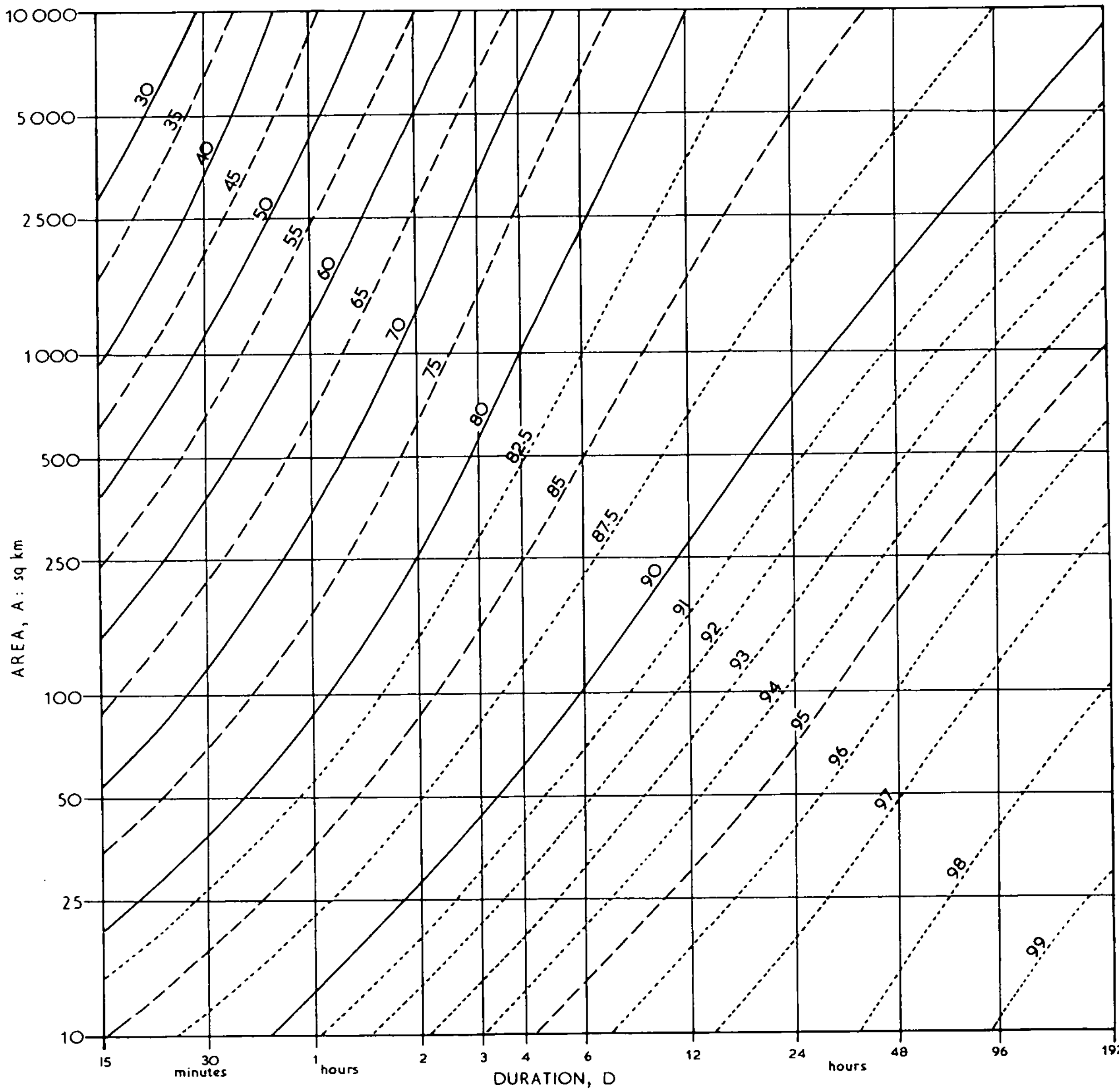


Table 5.2 Relation of ARF with duration ($D$) and area ($A$).

| Duration $D$ | Area $A$ (km²) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 5 | 10 | 30 | 100 | 300 | 1000 | 3000 | 10 000 | 30 000 |
| 1 min | 0.76 | 0.61 | 0.52 | 0.40 | 0.27 | — | — | — | — | — |
| 2 min | 0.84 | 0.72 | 0.65 | 0.53 | 0.39 | — | — | — | — | — |
| 5 min | 0.90 | 0.82 | 0.76 | 0.65 | 0.51 | 0.38 | — | — | — | — |
| 10 min | 0.93 | 0.87 | 0.83 | 0.73 | 0.59 | 0.47 | 0.32 | — | — | — |
| 15 min | 0.94 | 0.89 | 0.85 | 0.77 | 0.64 | 0.53 | 0.39 | 0.29 | — | — |
| 30 min | 0.95 | 0.91 | 0.89 | 0.82 | 0.72 | 0.62 | 0.51 | 0.41 | 0.31 | — |
| 60 min | 0.96 | 0.93 | 0.91 | 0.86 | 0.79 | 0.71 | 0.62 | 0.53 | 0.44 | 0.35 |
| 2 h | 0.97 | 0.95 | 0.93 | 0.90 | 0.84 | 0.79 | 0.73 | 0.65 | 0.55 | 0.47 |
| 3 h | 0.97 | 0.96 | 0.94 | 0.91 | 0.87 | 0.83 | 0.78 | 0.71 | 0.62 | 0.54 |
| 6 h | 0.98 | 0.97 | 0.96 | 0.93 | 0.90 | 0.87 | 0.83 | 0.79 | 0.73 | 0.67 |
| 24 h | 0.99 | 0.98 | 0.97 | 0.96 | 0.94 | 0.92 | 0.89 | 0.86 | 0.83 | 0.80 |
| 48 h | — | 0.99 | 0.98 | 0.97 | 0.96 | 0.94 | 0.91 | 0.88 | 0.86 | 0.82 |
| 96 h | — | — | 0.99 | 0.98 | 0.97 | 0.96 | 0.93 | 0.91 | 0.88 | 0.85 |
| 192 h | — | — | — | 0.99 | 0.98 | 0.97 | 0.95 | 0.92 | 0.90 | 0.87 |
| 25 days | — | — | — | — | 0.99 | 0.98 | 0.97 | 0.95 | 0.93 | 0.91 |

## 5.3 Suggestions for further reading

COURT A. (1961) Area–depth rainfall formulas. *Journal of Geophysical Research*, **66**, 1823–1831.

# 6 Storm profiles

## 6.1 Summary

Rainfall profiles are presented for United Kingdom summer and winter storms suitable for durations up to several days. In the analysis, storms were centred on the most intense part of the storm so that storm profiles could be compared more meaningfully.

The largest variations in profile are between individual storms in any particular classification, and by comparison, variations in profile with return period or duration are found to be relatively insignificant. Therefore the storm profiles have been ranked according to peak intensity, and standardised results for summer and winter seasons are presented in Tables 6.2 and 6.3 for storms classified in this way. Profiles were found to be essentially invariant with respect to storm duration, return period, and storm areal size. Regional differences and differences due to rainfall type are incorporated in, or confounded with, the seasonal differences, and the differences in percentile profiles within seasons.

## 6.2 Data examined

For various specified durations the occasions with greatest rainfall, i.e. largest storms, were considered according to the following scheme.

*a* In each of the 4 year periods 1951–54, 1955–58, 1959–62, 1963–66, 1967–70, the largest storms of duration 1, 2, 4, 6, 12, 24 clock hours and 4 rainfall days at each of 33 stations in the United Kingdom, tabulated hour by hour.

*b* Major flood producing 24 hour storms in England and Wales in the period 1961–70.

*c* Some of the largest 60 minute storms at Cardington and Winchcombe between 1957 and 1967 with rainfall totals available in 2 minute intervals.

## 6.3 Seasonal point profiles

### *6.3.1 Analysis of data*

In order to compare storm profiles, each storm was centred on the shortest duration which gave at least 50% of the rainfall. The mean profile for each duration was obtained for each of two seasons, summer (May to October), and winter (November to April). Detailed analysis was then done on 80 24 hour summer storms and 32 24 hour winter storms referred to in 6.2 (*a* and *b*); the storms of other durations were analysed separately (Section 6.4).

### *6.3.2 Summer 24 hour storms*

For each of the 80 24 hour summer storms (major 24 hour rainfall events) the proportion of the central 5 hour rainfall to 24 hour rainfall was noted, and this proportion was used to rank the 80 storms into four quartiles of profile peak, from flat to sharp, and the mean profile in each quartile was calculated. This subdivision displays the difference between rainfall types, very sharp peaks for thunderstorms, and flatter profiles for continuous rain. This subdivision also incorporates differences between regions, since the main differences between regions are confounded with the frequencies of rainfall type in each season.

In each quartile, the 20 storms were again centred on the shortest duration which gave at least 50% of the rainfall and the mean rainfall for each hour was obtained as a percentage of the centred 24 hour total. The percentages are given in Table 6.1 as cumulative percentages ($R$) against cumulative duration ($D$) about the storm centre.

**Table 6.1** Cumulative percentage rainfall (summer 24 hour storms) for the four quartiles of profile peakedness for varying ranges of duration about the profile peak.

| Cumulative duration about centre | | Quartile of profile peakedness | | | |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 |
| Hours | Percentage | Cumulative percentage rainfall | | | |
| 1 | 4.2 | 6.6 | 10.3 | 22.1 | 35.0 |
| 3 | 12.5 | 20.2 | 32.2 | 45.7 | 68.6 |
| 5 | 20.8 | 33.5 | 48.5 | 63.8 | 80.9 |
| 7 | 29.2 | 50.1 | 59.9 | 72.6 | 85.8 |
| 9 | 37.5 | 61.9 | 65.9 | 78.9 | 89.7 |
| 15 | 62.5 | 77.4 | 83.0 | 90.9 | 96.1 |
| 21 | 87.5 | 91.5 | 95.7 | 96.4 | 99.4 |
| 24 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |

From smoothed profiles for each quartile, the cumulative percentage rainfall was interpolated for cumulative percentage durations 4, 10, 20, 40, 60 and 80%. For each of these durations interpolation was then made to estimate the cumulative percentage rainfall for the 10, 25, 50, 75, 90 and 95 percentile points of profile peakedness. The profiles are given in Table 6.2, and are shown in Figure 6.1.

**Table 6.2** Summer storm profiles for point rainfall.

| Cumulative percentage duration | Percentiles of profile peakedness: 10 | | 25 | | 50 | | 75 | | 90 | | 95 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $R\%$ | Prop'n of $I$ | $R\%$ | Prop'n of $I$ | $R\%$ | Prop'n of $I$ | $R\%$ | Prop'n of $I$ | $R\%$ | Prop'n of $I$ | $R\%$ | Prop'n of $I$ |
| 0 | 0 | | 0 | | 0 | | 0 | | 0 | | 0 | |
| 2 | | 1.5 | | 2.2 | | 3.75 | | 6.0 | | 9.0 | | 11.0 |
| 4 | 6 | | 9 | | 15 | | 24 | | 36 | | 44 | |
| 7 | | 1.5 | | 2.2 | | 3.0 | | 4.0 | | 4.5 | | 5.0 |
| 10 | 15 | | 22 | | 33 | | 48 | | 63 | | 74 | |
| 15 | | 1.5 | | 1.9 | | 2.1 | | 2.1 | | 1.9 | | 1.6 |
| 20 | 30 | | 41 | | 54 | | 69 | | 82 | | 90 | |
| 30 | | 1.4 | | 1.25 | | 1.0 | | 0.65 | | 0.5 | | 0.3 |
| 40 | 58 | | 66 | | 74 | | 84 | | 92 | | 96 | |
| 50 | | 0.9 | | 0.7 | | 0.6 | | 0.4 | | 0.2 | | 0.1 |
| 60 | 76 | | 80 | | 85 | | 91 | | 96 | | 98 | |
| 70 | | 0.7 | | 0.6 | | 0.4 | | 0.3 | | 0.1 | | 0.1 |
| 80 | 89 | | 91 | | 93 | | 96 | | 98 | | 99 | |
| 90 | | 0.5 | | 0.4 | | 0.3 | | 0.2 | | 0.1 | | |
| 100 | 100 | | 100 | | 100 | | 100 | | 100 | | 100 | |

$R\%$, cumulative percentage of total storm rainfall; Prop'n of $I$, proportion of the mean intensity of the total storm.
The 95% (sharpest) profile is one which will have a flatter profile on 95% of occasions (Figure 6.1), i.e. will have a sharper profile on 5% of occasions; e.g. for the sharpest 5% of summer storm profiles at least 90% of the rainfall will occur in 20% of the storm duration.

For example, the median profile (50 percentile) shows an increase in cumulative rainfall from 15 to 33%, between cumulative durations 4 and 10% (2 and 5% on either side of storm centre), i.e. rainfall increase of 18% for a duration increase of 6%, and the mean intensity is the ratio $(18/6) = 3.0$ times the mean intensity $I$ for the storm duration. The peak intensity, for percentage duration 0–4, i.e. 0–2% on either side of centre, is $3.75I$.

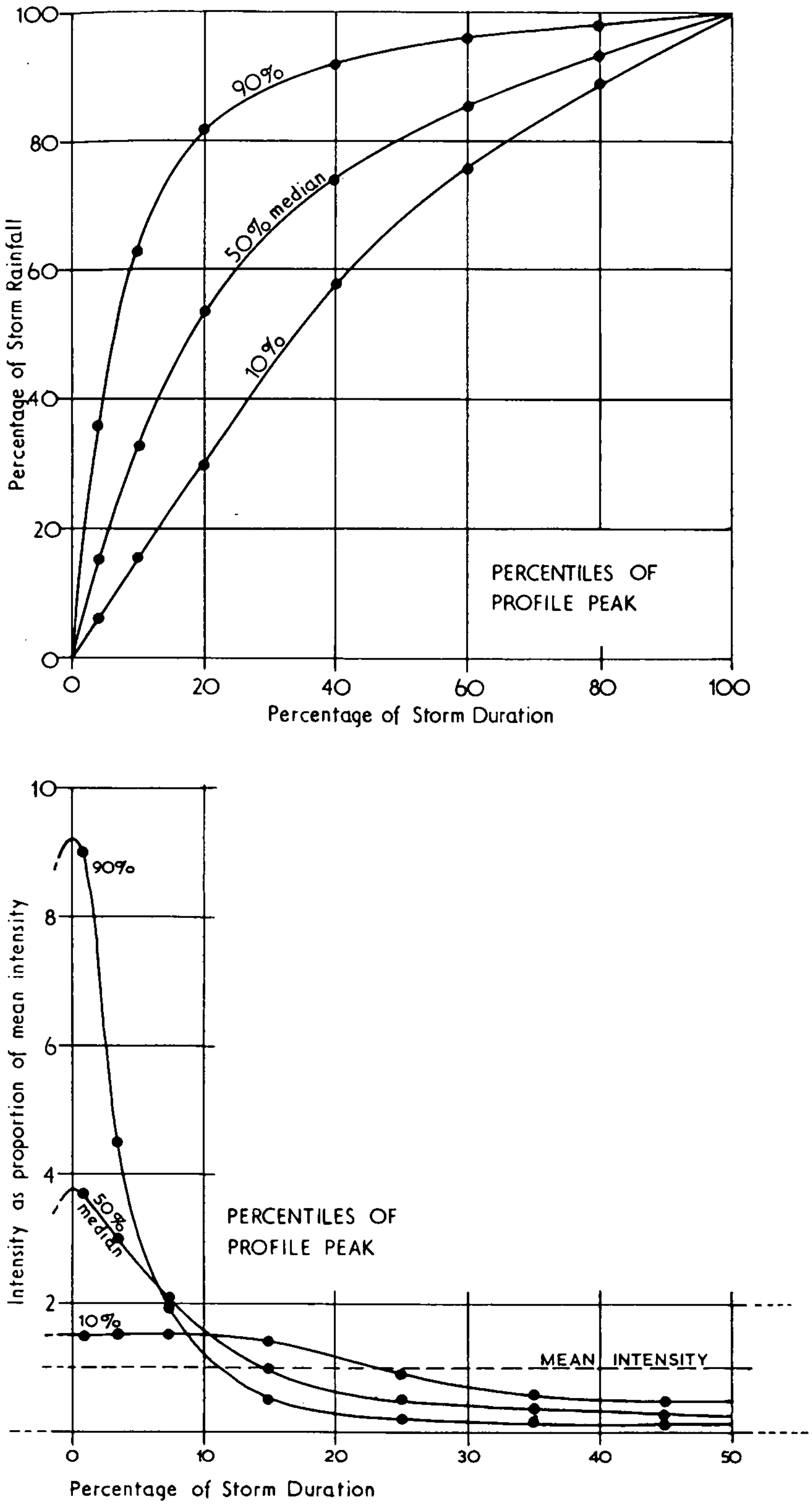



Fig 6.1 Summer storm profiles.

Only 10 % of profiles are more flat than the profile in the first column, which shows a peak intensity of $1.5I$; 25 % are more flat than the profile of the second column (or 75 % more peaked), with peak intensity $2.2I$;

only 5% of profiles are more strongly peaked than the profile in the last column, with peak intensity slightly greater than $11.0I$.

### 6.3.3 *Winter 24 hour storms*

The 32 major 24 hour winter storms were analysed in the same way as the 80 24 hour summer storms of 6.3.2. Table 6.3 gives the winter storm profiles. They are also shown in Figure 6.2.

**Table 6.3** Winter storm profiles for point rainfall.

| Cumulative percentage duration | Percentile of profile peakedness: 10 | | 25 | | 50 | | 75 | | 90 | | 95 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $R$% | Prop'n of $I$ | $R$% | Prop'n of $I$ | $R$% | Prop'n of $I$ | $R$% | Prop'n of $I$ | $R$% | Prop'n of $I$ | $R$% | Prop'n of $I$ |
| 0 | 0 | | 0 | | 0 | | 0 | | 0 | | 0 | |
| 2 | | 1.3 | | 1.7 | | 2.0 | | 2.5 | | 3.5 | | 4.5 |
| 4 | 5 | | 7 | | 8 | | 10 | | 14 | | 18 | |
| 7 | | 1.3 | | 1.7 | | 1.9 | | 2.3 | | 3.2 | | 4.2 |
| 10 | 13 | | 17 | | 19 | | 24 | | 33 | | 43 | |
| 15 | | 1.3 | | 1.6 | | 1.8 | | 2.1 | | 2.5 | | 2.7 |
| 20 | 26 | | 33 | | 37 | | 45 | | 58 | | 70 | |
| 30 | | 1.3 | | 1.4 | | 1.45 | | 1.4 | | 1.2 | | 0.9 |
| 40 | 52 | | 61 | | 66 | | 72 | | 81 | | 88 | |
| 50 | | 1.0 | | 0.9 | | 0.8 | | 0.65 | | 0.4 | | 0.3 |
| 60 | 73 | | 79 | | 82 | | 85 | | 90 | | 94 | |
| 70 | | 0.8 | | 0.55 | | 0.5 | | 0.4 | | 0.3 | | 0.2 |
| 80 | 88 | | 90 | | 92 | | 94 | | 96 | | 98 | |
| 90 | | 0.6 | | 0.5 | | 0.4 | | 0.3 | | 0.2 | | 0.1 |
| 100 | 100 | | 100 | | 100 | | 100 | | 100 | | 100 | |

$R$%, cumulative percentage of total storm rainfall; Prop'n of $I$ = proportion of the mean intensity of the total storm.
The 95% (sharpest) profile is one which will have a flatter profile on 95% of occasions (Figure 6.2), i.e. will have a sharper profile on 5% of occasions; e.g. for the sharpest 5% of winter storm profiles at least 70% of the rainfall will occur in 20% of the storm duration.

## 6.4 Variability of profile with storm duration

Storm profiles were determined for 10 60 minute summer storms from Cardington and Winchcombe 2 minute data, and 4, 6, 12 hour and 4 day storms at stations in south east England and the Midlands.

For summer storms the standardised mean profile of cumulative proportional rainfall ($R$) against cumulative proportional duration ($D$), $R$ and $D$ increasing from zero to unity, was calculated. Some of the results are presented in Table 6.4, and show that there was no systematic variation with storm duration. A similar analysis for winter storms led to the same conclusion.

**Table 6.4** Proportion of total rainfall for a given proportion of storm duration.

| Storm duration | Proportion of storm duration: 0.25 | 0.50 | 0.75 |
|---|---|---|---|
| 4 rain days | 0.64 | 0.79 | 0.87 |
| 24 clock hours | 0.63 | 0.78 | 0.86 |
| 12 clock hours | 0.55 | 0.76 | 0.86 |
| 6 clock hours | 0.56 | 0.78 | 0.88 |
| 60 minutes | 0.57 | 0.77 | 0.86 |

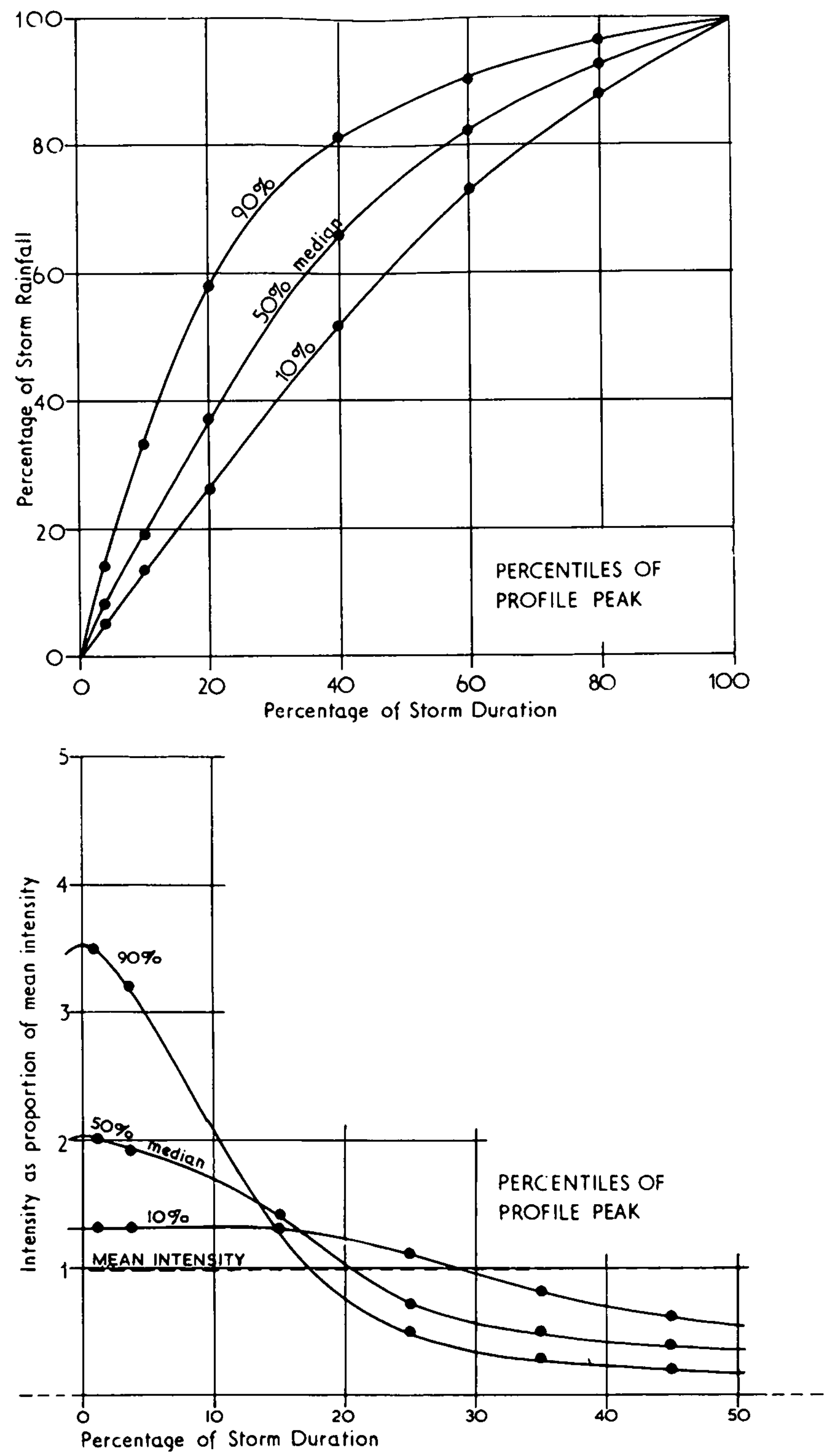



**Fig 6.2** Winter storm profiles.

## 6.5 Variability of storm profile with return period

For each of eight stations in the United Kingdom, the five 4 year maximum 24 hour storms were ranked in order of magnitude from 1 (low) to 5 (high):

the ranks correspond to return periods of 2.5, 4, 6, 11 and 29 years. The median storm profile did not vary systematically with the return period (Table 6.5).

For each of the five ranks the eight stations were classified into three groups according to percentage value of rainfall for the central part of the storm, the two flattest, the middle four and the two with highest peak, with group means corresponding to 12.5, 50, 87.5 percentile of peak. For each of these percentiles there was no significant variation in the profile with return period.

**Table 6.5** Proportion of total rainfall for given proportions of storm duration and given return periods ($T$).

| Rank | $T$(years) | Proportion of storm duration | | | |
|---|---|---|---|---|---|
| | | 0.125 | 0.375 | 0.625 | 0.875 |
| 1 | 2.5 | 0.48 | 0.75 | 0.85 | 0.93 |
| 2 | 4 | 0.42 | 0.66 | 0.79 | 0.87 |
| 3 | 6 | 0.45 | 0.69 | 0.70 | 0.87 |
| 4 | 11 | 0.37 | 0.70 | 0.80 | 0.87 |
| 5 | 29 | 0.45 | 0.77 | 0.87 | 0.94 |

## 6.6 Variability of storm profile with region

The variation of storm profiles depends on the geographical location and this variation is confounded with the frequencies of rainfall type in each season. It was not possible to quantify the independent effect of geographical location, i.e. topography, land–sea relation, etc., on the frequencies of profiles exceeding a particular peakedness.

The storm profiles presented in Tables 6.2 and 6.3 are applicable to most regions of the United Kingdom. The summer profiles, however, should be applied with caution to storms in mountainous areas. For example the 95 percentile summer profile (Table 6.2) gives a profile much too peaky for mountainous areas.

## 6.7 Areal profiles

A brief study was made of 15 major summer 24 hour storms for an area of 8000 km$^2$ centred on the Chilterns during the period 1961–69. For each storm the areal fall was estimated for each clock hour from a network of recording raingauge stations (used for the ARF estimations, Chapter 5). The analysis for the areal storms was done in the same way as for the point summer storms described in 6.3; but using three terciles each of five storms. The cumulative percentage rainfall, and corresponding storm intensity as a proportion of mean intensity, for this areal study are in remarkably close agreement with the corresponding values for the point storms. Differences are small compared with differences between percentiles within either the point storms (Table 6.2) or areal storms, except that the highest peaks for areal rainfall are slightly flatter than the corresponding point peaks.

Since for practical engineering purposes the corresponding areas and durations for which profiles are required are those for which there is a great degree of areal coherence, areal profiles may be little different from the appropriate point profiles.

# 7 Snow cover and snowmelt

## 7.1 Summary

A rough estimate is made of rare snowmelt rates applicable to most lowland catchments in the United Kingdom, using return periods of maximum air temperature, a temperature–snow depth depletion relationship, and assumed values of snow density. Frequencies of snow depth are calculated for an 'average' place in the United Kingdom, and 2 year snow depth is mapped. Relationships between cumulative 3 hour temperatures and return period are presented for use with Chapter 7 of Volume I. Reference is made to the reports of other workers, whose results are based on the analysis of snow data in countries where a deep layer of snow regularly accumulates and melts each year.

## 7.2 Introduction

In 1967 the Institution of Civil Engineers Committee on Floods in their report (para. 56) recommended that a flood study team should:
*a* examine records of historic storms, snow cover and floods to assess the importance, by regions, of the snowmelt contribution to floods, particularly in the context of frequency studies;
*b* review existing techniques of studying snowmelt, and assess their applicability to British conditions; and
*c* prepare a suitable method of estimating maximum snowmelt rates for inclusion in probable maximum flood studies.
The Committee also recognised (para. 85) that although snow cover and snowmelt are 'an important aspect of flood hydrology on which very little work has been done in the United Kingdom', there are 'few reliable quantitative data'.

This shortage of data may well have been fostered by the traditional British attitude that snow is rare and not important in this country. Although this may well have an element of truth in it for small lowland catchments, it is certainly not true for the major rivers of this country, many of which recorded their maximum flood following a rapid snowmelt. It was in fact pointed out by the Committee that 'these studies will certainly indicate the need for more elaborate and widespread measurements of snow cover and snow moisture contents'.

In a previous report the Meteorological Office (1968a) calculated point snowmelts at Buxton, in the southern Pennines. It is unfortunate that so few meteorological data are available for mountainous parts of the country, and this has seriously limited the work in this chapter. High ground stations in England and Wales could not provide a sequence of years of data on snow cover and temperature, although it is possible that some Scottish stations could provide this for future research.

Chapter 6 of the World Meteorological Organisation Guide to Hydrometeorological Practices (1965) devotes several pages to the problem of estimating the peak flow during a snowmelt event, but is unable to give much helpful advice to an engineer in this country, where snow cover, even on high ground, is so variable and unreliable.

Although the major effort of the small Meteorological Flood Studies Team has been concentrated on rainfall, especially the depth–duration–return period–area relationships, a chapter has been prepared and is presented here on some of the hydrometeorological aspects of snow cover and snowmelt. Further work is presented in Chapter 7, Volume I, and some of the results here for the return period of some temperature parameters are of use with that chapter.

### 7.3 Snowmelt hydrology

During many winters most parts of the United Kingdom experience only negligible amounts of snow, but nevertheless from time to time snow takes on an important role in a major river flood, usually after a severe winter, such as 1947 and 1963 as described by Bleasdale (1973). In 1947 a 2 months' accumulation of snow thawed rapidly in midMarch and contributed very substantially to large scale severe floods over many parts of the country. The amount of snow accumulated in 1962/3 was appreciably smaller in most parts, but produced notable floods, especially in north east England.

Information on snow depth after historic storms can be found in journals such as British Rainfall or Meteorological Magazine but, after heavy snow, depths are notoriously difficult to measure accurately because of drifting. The largest snowfalls usually occur over high ground, but snow depths of 50 cm have been recorded in many parts at some time during the past 100 years; for example, the Isle of Wight, January 1881; Oxford area, February 1888; Kent, December 1927. The melting of such a depth of snow may take place over several weeks or more, as indicated by Lowndes (1971).

In estimating potential snowmelt volumes it is necessary to know the water content of the snow, which can be calculated from the depth of snow and its density. However, it is difficult to estimate potential snowmelt volumes for a catchment because of the variability of depth and density, especially density. The density of freshly fallen snow is usually between 0.05 and 0.20 g cm$^{-3}$, whilst the traditional accepted water equivalent for one foot (0.3 m) of snow is one inch (25.4 mm) of rain (i.e. a density of 0.083 g cm$^{-3}$).

Under the weight of fresh snow, or just with the passage of time, snow crystals fracture and the snow compacts with a consequent increase in density, as described for example by Rey (1970). Air temperature above 0°C and falling rain both help to increase the density of lying snow.

Average densities of lying snow ought to vary only a little from one part of the country to another, but since the density is known to increase with duration of snow cover, and snow persists longest over high ground, density probably increases with altitude as well. Although an average density was calculated from only 1 year's data here, it was realised that after a long wintry spell such values would be less appropriate than values from countries where winters are usually more severe. During a snowy winter in the German Democratic Republic, Grasnick (1967) found densities rising to between 0.26 and 0.32 g cm$^{-3}$, while with a snow depth of only 15 cm, Hegedus *et al.* (1967) in Hungary, found densities rising to a fairly steady value around 0.23 g cm$^{-3}$ after 2 weeks, and reaching 0.33 during the thaw.

The occurrence of heavy rain during snowmelt can increase the snowmelt flood peak considerably, and the extra volume due to rain often needs to be added to the snowmelt flood peak. Usually the height of the snowmelt contribution to the flood peak is limited by the depth of snow available for melt. However, when depths are large, the snowmelt rate, and consequently the snowmelt flood peak, is limited instead by the meteorological parameters; in fact, mainly by the air temperature.

General theoretical equations for snowmelt rates, such as that given by the United States Army (1956), usually express snowmelt rate as a function of wind speed, humidity, rainfall, and solar radiation, as well as air temperature. In the United Kingdom, rapid thaws usually occur with mild, moist, cloudy airstreams with much mist and low cloud. An equation by Bruce & Sporns (1963) has been modified for use in the Meteorological Office to estimate snowmelt on days with low cloud base and complete cloud cover, *viz.*:

$$M = T(1.32+0.394kV)-0.30kV(T-T_2)+0.0126PT \qquad (7.1)$$

where $M$ is daily snowmelt (mm), $T$ is mean air temperature in the screen (°C), $T_2$ is dew point in the screen (°C), $V$ is the wind speed at a height of 10 m (knots), $P$ is the day's rainfall (mm), and $k$ is an empirical friction factor, varying from 0.3 in heavily forested parts to 1.0 in very exposed parts, with typical value around 0.6.

When the wind is light the major term in Equation (7.1) is the air temperature. A preliminary analysis for the work in this chapter confirmed that the most important factor is air temperature, with the best snowmelt days also having high relative humidities (more than 80%) and cloudy skies. As a result of these findings the subsequent work concentrated almost entirely on air temperatures.

Snowmelt runoff and air temperature relationships are presented in Chapter 7 of Volume I: calculation of the return period of various air temperatures during snow cover allows estimates to be made of the return period of various snowmelt runoffs. The two temperature parameters used in this section are maximum air temperature and cumulative 3 hour temperature with snow cover, cumulative 3 hour temperatures simply being obtained by adding together the air temperatures recorded at the synoptic hours (i.e. 0300, 0600, 0900 GMT etc.). The latter was for use with Volume I; the former was used for making quick independent estimates of snowmelt.

Relations between snowmelt rates and some kind of temperature parameter have been calculated by various authors for snowy catchments in various countries, and these may be contrasted with the relation found for this country between snowmelt rate and maximum temperature. Pahaut (1970) finds a linear relation of 4.05 mm day$^{-1}$ °C$^{-1}$ for water equivalents of more than 160 mm, Kinosita *et al.* (1967) find a similar value of 4–5 mm day$^{-1}$ °C$^{-1}$ for a snowy upland catchment in Japan, while Abaljan (1972) also finds a similar value close to 5 mm day$^{-1}$ °C$^{-1}$ at altitudes between 1400 and 4000 m in the Varzob river basin in Central Asia.

After the initial analysis of maximum temperature for days with snow lying, a further analysis was carried out for cumulative temperatures for a smaller sample of stations. However, there was only a small range in the station heights with no station on high ground, and no significant correlation was evident between altitude and the occurrence of high temperatures during snow cover.

## 7.4 Data available and methods of analysis

### *7.4.1 Maximum snow depths*

The depth of snow at 0900 GMT began to be recorded regularly at some meteorological stations around 1947, details of which have been collected together by Burns (1964) for stations in Scotland, and by Dewar (1971) for stations in England, Wales, and Northern Ireland. From this information the maximum snow depth–return period relationship may be estimated for some 100 stations for the years 1946–64 (18 winters). The median of the values gives the annual maximum snow depth which is equalled or exceeded once in 2 years, and these values were plotted on a map, and isopleths drawn (Figure 7.2). It is hoped that this map can usefully serve as a standard against which snow depths for other return periods may be compared. For example, it is assumed that for any return period the smallest depth of snow is found on western coasts, which is where the smallest values occur on the once in 2 year map. However, the map may well be in error over some of the more mountainous parts of the country because of the shortage of basic data.

Quartile analysis of the annual maximum snow depth data was carried out by the methods used in Chapter 2, and the median of all the stations was found for each quartile value—in effect, the quartile values were found for what could be called an 'average' station. These values were assumed to be indicative of the shape of the depth–return period relationship at any station, and it was hoped that snow depth grows with return period from the 2 year value in the same way as rainfall grows from the 5 year value of rainfall in Chapter 2. Table 7.1 gives the snow depths for various return periods read off the curve for the 'average' station. If it is extrapolated, it is interesting to note that a 50 cm depth of snow has a return period at the 'average' station close to 200 years.

**Table 7.1** Snow depth–return period values at the 'average' station.

| Return period (years) | Snow depth (cm) |
|---|---|
| 2 | 5.6 |
| 5 | 12.2 |
| 10 | 17.3 |
| 20 | 23.3 |
| 50 | 33.0 |
| 100 | 43.0 |

Since the limit to the maximum volume of snowmelt water running off a catchment during large snowmelt events is determined by the meteorological factors, rather than the initial snow depth, it was considered more valuable to look at the return period for the meteorological factors during snow cover.

### 7.4.2 *Density of lying snow*

Water equivalents and densities of lying snow have been measured regularly at most meteorological stations since the winter of 1964. The observer takes three sample cores of snow from an undrifted part of the snow field at 0900 GMT each morning when snow is measurable, and melts them indoors. He also notes the depth of undrifted snow at the same time, and the density of the snow can then be calculated easily. In other countries such snow cores are weighed with a spring balance, often in the snow field itself. Records of snow density and water equivalent for this country are kept at the Meteorological Office, Bracknell.

Data from some 20 stations were analysed for this study for the winter of 1970/71, in order to get some idea of the average and range of snow densities. For each station with more than 2 cm of snow lying at 0900 on more than three mornings a median density of snow was calculated, by taking the mean of the middle half of the ordered values. Similarly for each of 11 mornings when five or more stations had more than 2 cm of snow lying the median density was calculated in the same way. Both median values give an 'average' value of 0.13 g $cm^{-3}$, although large variations were observed not only from day to day, but also from station to station (values ranged from 0.064 at Gatwick Airport to 0.253 at Manston, Kent) probably reflecting the low quality of some of the data.

During the winter of 1962/63 the Building Research Station made their own measurements of snow density and water equivalents near Watford, and Lacy (1963) reports that the density stabilised after several days to a value between 0.25 and 0.30 g $cm^{-3}$, while the temperature was near or below freezing point, but rose to a mean value of 0.36 g $cm^{-3}$ with thawing conditions.

Snow density data were available for several meteorological stations in Germany during the winter of 1962/63, one of which, Freudenstadt in the Schwarzwald, had snow lying continuously from 16 November until 24 March. Deep snow lay from 17 December until 18 March, with a depth of 70 cm for much of that time and a maximum depth of 113 cm on 21 February. Such conditions were considered close to the severest possible in the United Kingdom. The density of the lying snow quickly stabilised after the heavy snow in midDecember to a value of 0.29 g $cm^{-3}$, but during the warmer conditions of March the mean density was 0.36 g $cm^{-3}$, whilst during the final week of snow cover, when there was a rapid thaw and heavy rains, the density reached a value of 0.42 g $cm^{-3}$. These values are very similar to others referred to in Section 7.3.

### *7.4.3 Return periods of high temperatures with snow lying*

Once every 3 hours the observing stations run by the Meteorological Office note the presence or absence of snow, whether the snow covers more or less than half of the ground, and whether the snow is loose and dry or wet. Some 15 years of such meteorological data are available on magnetic tape for about a dozen stations in the United Kingdom. When snow covered more than half of the ground, 3 hour temperatures were noted for five stations (Figure 7.1) for the winters 1957–71 (14 years of data). The annual maximum cumulative 3, 6, 12, 18, 24 and 36 hour temperatures were noted for each station, and the values ranked and plotted on a Gumbel diagram. Although there is no certainty that the points ought to form a straight line plot, a straight line was drawn through the upper half of the values, which must give a reasonable approximation to the truth for return periods of less than 20 years.

The largest values at the five stations occur at Aberdeen, and the lowest at Gatwick, suggesting a possible variation with latitude. No correlation is evident between temperatures and altitude, although the sample of only five stations is too small to show very much.

The annual maxima for the five stations were collected together to form one data set of 70 station years, and values were replotted on a Gumbel diagram. A straight line was drawn through the data points, so that estimates could be made, not only of the 20 year cumulative temperatures, but also of the temperatures with return period up to 100 years for different durations when snow is lying (Figure 7.3). Although this analysis was not


**Fig 7.1** Location of stations for temperature studies. +, cumulative temperature; ●, maximum 3 hour temperature; ×, changes in snow depth with temperature.

very extensive, it is intended to be of value in connection with the temperature–snowmelt studies presented in Chapter 7 of Volume I.

Maximum recorded 3 hour temperatures at a station with snow lying are more easily available than the cumulative temperatures, and data from 14 stations, each with about 15 years of record, were examined and annual maximum temperatures were collected and analysed to determine the temperature with return period of 5 years. These individual station values are given in Table 7.2.

**Table 7.2** Station values of once in 5 year maximum 3 hour temperature with snow lying at the station.

| Station name | Nat. grid ref. | Altitude (ft) | 5 year temp (°C) |
|---|---|---|---|
| Aberdeen (Dyce) | NJ 883125 | 190 | 5.61 |
| Acklington, Northumberland | NU 225007 | 140 | 5.17 |
| Ballykelly, Co. Londonderry | IC 624234 | 10 | 5.33 |
| Birmingham (Elmdon) | SP 171837 | 320 | 6.34 |
| Bristol (Filton) | ST 598802 | 190 | 4.72 |
| Chivenor, Devon | SS 494347 | 20 | (3.55)† |
| Coltishall, Norfolk | TG 262229 | 50 | 6.02 |
| Finningley, Yorks. | SK 658995 | 34 | 5.59 |
| Gatwick, Surrey | TQ 265407 | 190 | 5.40 |
| Kirkwall, Orkneys | HY 483076 | 80 | 4.63 |
| Manby, Lincs. | TF 391869 | 50 | 4.68 |
| Marham, Norfolk | TF 739087 | 80 | 4.38 |
| Nottingham (Watnall) | SK 503456 | 390 | 6.29 |
| Wittering, Northants. | TF 048032 | 260 | 4.49 |
| Median | | | 5.24 |

†Only 6 years with snow.

Analysis of the combined annual 3 hour maxima for the equivalent 150 station years was carried out using quartile analysis again, and these results were also plotted on a Gumbel diagram. A straight line was drawn through these points, and the values for various return periods are presented in Table 7.3. The Gumbel line from all these data was found to coincide almost exactly with the 3 hour line from just the five stations used in the cumulative temperature study.

**Table 7.3** Annual maximum temperature with return period for 'average' station when snow is lying.

| Return period (years) | Max. 3 hour temp. (°C) |
|---|---|
| 2 | 4.2 |
| 5 | 5.4 |
| 10 | 6.2 |
| 25 | 7.2 |
| 50 | 7.9 |
| 100 | 8.6 |

### *7.4.4 An estimate of a rare snowmelt rate*

An analysis of changes in snow depth with maximum temperature was combined with estimates of snow density to produce an equation relating snowmelt and maximum temperature. Association with the maximum temperature—return period relationship in Table 7.3 gives a quick, rough estimate of the point snowmelt for the different return periods. Over fairly uniform catchments with little mountainous area much of the catchment may be assumed, at worst, to be contributing snowmelt water at this same rate.

Maximum air temperatures and 24 hour changes in snow depth were noted for 15 years, mostly 1953–67, for nine stations in England and Wales. Inevitably the data were gathered both from short snowmelt events, where all the snow melted in just over 24 hours, and from snowy winters when the snow cover persisted for a week or more. The values were plotted on a diagram, and indicated a linear rate of increase of depth depletion with maximum temperature, with no depth depletion at 0°C. This linear rate of increase gave a depth depletion rate of 1.21 cm of snow $day^{-1}$ $°C^{-1}$, or

$$\text{Point snow melt} = 12.1\ \rho \text{ mm water day}^{-1}\ °\text{C}^{-1} \qquad (7.2)$$

where $\rho$ is the density of lying snow.

Equation (7.2) can be used with a 'typical' snow density of 0.13 g $cm^{-3}$ from Section 7.4.2, to give a point melt rate of 1.56 mm water $day^{-1}$ $°C^{-1}$. If this equation is used with a density of 0.30, more typical of a persistent snow cover, then this gives a point melt of 3.6 mm water $day^{-1}$ $°C^{-1}$. Although this is assuming that the snow depth depletion rate is the same in both cases, nevertheless the value of 3.6 is quite close to the values of 4.05, 4–5, and 5 mm water $day^{-1}$ $°C^{-1}$ quoted in Section 7.3 from other sources. It should, however, be mentioned that the temperatures quoted elsewhere are mean or cumulative temperatures, while the temperatures used above are maximum temperatures. For good snowmelt conditions, with wind and high humidities, the air temperature range is small, and the differences between the two measures of temperature are much less than might be expected.

The 3 hour maximum temperature relationship with return period from

7.4.3 could be combined with Equation (7.2) above and some likely values of snow density to give values of snowmelt rates. It was thought that the use of two different types of maximum temperature, i.e. the maximum value recorded at any time, and the maximum value recorded at a 3 hour observation, makes little difference to the results.

As stated in 7.4.2 snow densities may reach 0.40 g $cm^{-3}$ in extreme conditions of deep snow and a rapid thaw. Using this value with the estimated 100 year maximum temperature from Table 7.3, an estimate is obtained for a rare snowmelt rate of 42 mm $day^{-1}$. With depths of snow greater than 25 cm, this snowmelt rate could continue for 2 or 3 days.

## 7.5 Results

From Figure 7.2 it can be seen that in half of all winters in nearly all parts of the United Kingdom, a depth of snow greater than 5 cm accumulates at some time, whilst a substantial part of the country has depth greater than 10 cm, and more than 30 cm accumulates in some of the more northern mountainous areas. In a severe winter, snow can accumulate to a depth of 50 cm or more almost anywhere in the country, with the snow cover persisting for many weeks, and possibly months. Such conditions are much more likely in mountainous parts, and Figure 7.2 indicates the likely snow depth distribution for any return period. Table 7.1 gives maximum snow depth against return period for an 'average' station; it is assumed that this rate of increase with return period applies equally well to all parts of the country, with snow depth increasing with return period from the 2 year value of Figure 7.2, in the same way as rainfall increases from the 5 year rainfall values of Chapter 2.

When snow is deep and persistent for several weeks, densities usually change from the 'average' value of 0.13 g $cm^{-3}$ to a value around 0.30, and occasionally during a rapid thaw may possibly exceed 0.40 g $cm^{-3}$. Such large densities produce much larger snowmelt volumes than are calculated from depth depletions with large return periods and more 'average' values for density.

The cumulative temperatures for different return periods presented in Figure 7.3 enable estimates to be made of cumulative runoff for various return periods ( Volume I, Chapter 7). Although none of the stations used to compile the temperature return period relationship, given in Figure 7.3, were in mountainous terrain, it is suggested that the return periods for cumulative temperature in mountainous parts are similar to those on low ground, and errors from the use of Figure 7.3 will not be too large.

Further work on maximum temperature and return periods during snow cover, on temperature and snow depth depletion, and on densities of snow allows rough estimates of a rare snowmelt rate to be made for the United Kingdom. Using a density of 0.40 g $cm^{-3}$ and the 100 year maximum temperature, a snowmelt rate of 42 mm $day^{-1}$ is estimated. Over lowland catchments with snowmelt fairly uniform the whole of a catchment may be expected to contribute at this same rate. The results in Volume I, Chapter 7 indicate that small upland catchments can have even greater snowmelt rates.

Some previous work carried out by the Meteorological Office (1968) for the Trent catchment above Nottingham, when calculations using Equation (7.1) and a straight line on a Gumbel diagram extrapolated to 1000 years gave the 5 year melt as 15.1 mm $day^{-1}$, the 25 year as 25 mm $day^{-1}$,

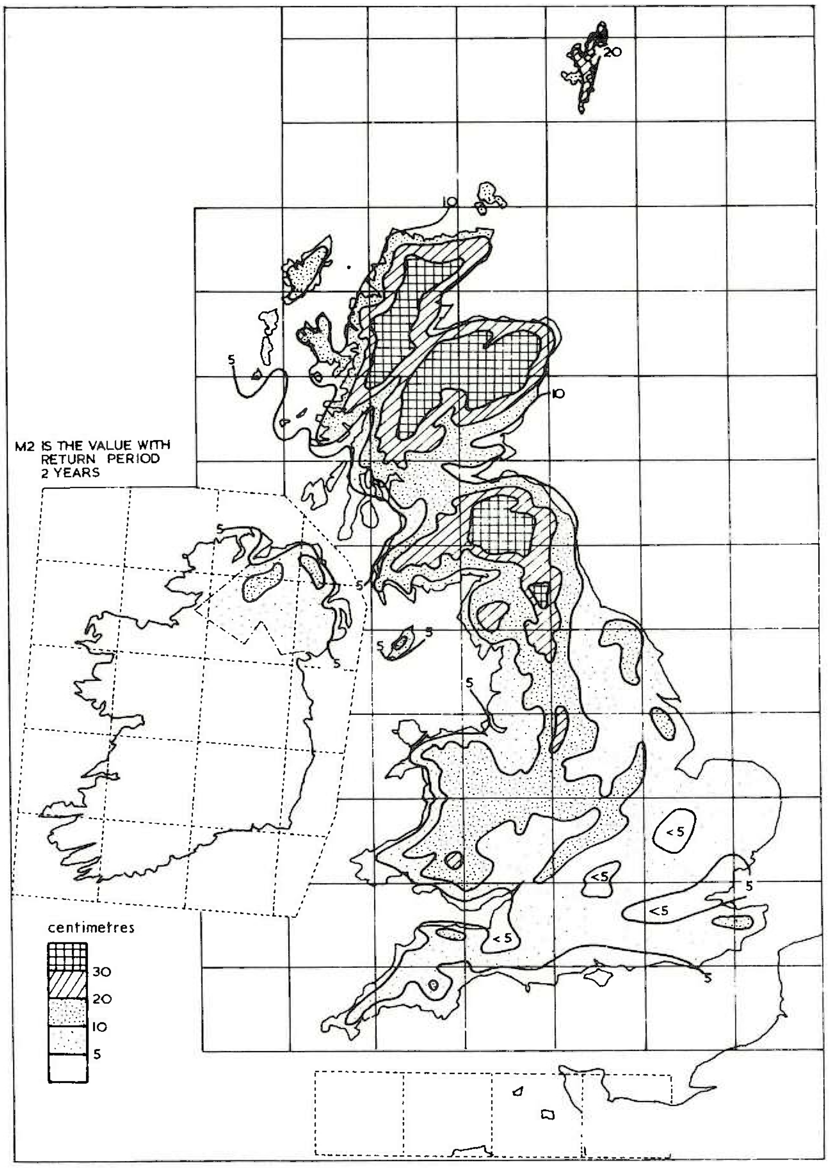
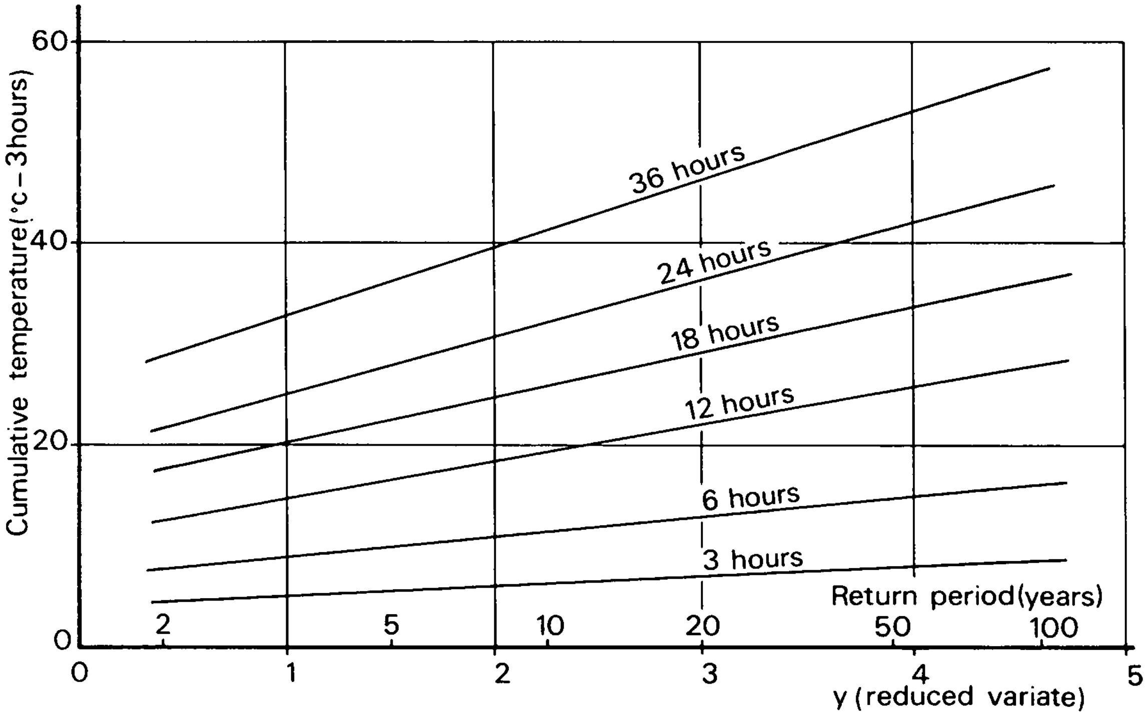



Fig 7.2 Simplified map of M2 snow depth: median annual maximum snow depth, 1946–64.

and the 100 year as 33 mm day$^{-1}$. The equivalent total snowmelt was estimated for the duration of 3 days as 32, 51 and 69 mm for the 5, 25 and 100 year point snowmelt respectively. The 100 year value of 33 mm day$^{-1}$ derived for the Trent is less than the rare snowmelt rate calculated in this chapter. Nevertheless, the Trent value was of the right order of magnitude.

The occurrence of rain during snowmelt is obviously important in its enhancement of river flow rates, and one can visualise the combination of a large snowmelt and unusually heavy rains giving extremely large river flows. It is planned to extend the present work to include this very important aspect of the subject, but meanwhile Chapter 7 of Volume I is recommended.

**Fig 7.3** Return period of various cumulative temperatures (when snow is lying).




## 7.6 Concluding remarks

Much work still remains to be carried out on the meteorological aspects of snowmelt, especially for upland catchments, where suitable observations are so scarce. Investigations are still needed into the coincidence of unusually large rainfall events and large snowmelt events, and into the coincidence of heavy rain and frozen ground conditions, as recommended by the ICE Committee on Floods, both of which are of great interest.

In no sense is the work complete, and much more needs to be done to help in this difficult and yet important subject of snow cover and snowmelt.

# 8 Examples of rainfall estimates for the Tyne and Wansbeck catchments

## 8.1 Introduction

### *8.1.1 Choice of examples*

The catchments of the rivers Tyne and Wansbeck in Northumbria were chosen to illustrate the methods of rainfall estimation described in earlier chapters. Both catchments have very varied topography and rainfall, with high ground and high AAR (average annual rainfall) in the west of each catchment, and with low AAR in the east of each catchment where the rivers enter the North Sea. The Tyne catchment is fairly large, area about 3000 km$^2$; the Wansbeck catchment is rather small, about 350 km$^2$. Both have experienced large floods.

### *8.1.2 Computational programme*

Let us suppose that there is a need to know the catchment areal rainfall for a given duration $D$ and given return period $T$, and that a likely time profile of the storm rainfall is wanted. It may also be supposed that an estimate of the maximum areal rainfall in duration $D$ is required.

Place a grid of equally spaced points over the catchment. Some 20–60 points would suffice. It would be advantageous to subdivide the catchment into two or three equal areas with relatively homogeneous AAR within each. At each point of the grid, estimate a value for

*a* AAR from Figure 3.1.

*b* 2 day M5 from Figure 3.2.

NB 2 day M5 is the rainfall in two consecutive rainfall days which is equalled or exceeded once in 5 years. In areas where it is difficult to interpolate for 2 day M5 it may be desirable to estimate the ratio (2 day M5)/AAR from Figure 3.3 and, using AAR, evaluate 2 day M5.

*c* (60 minute M5)/(2 day M5) from Figure 3.5.

NB 60 minute M5 is the rainfall within a duration of 60 minutes which is equalled or exceeded once in 5 years.

*d* (25 day M5)/AAR from Figure 3.4.

NB 25 day M5 is the rainfall within a 25 day period which is equalled or exceeded once in 5 years. From the value of AAR we then obtain 25 day M5.

Then for each of the two or three fairly homogeneous subareas, of equal area, we take means of AAR, 2 day M5, (60 minute M5)/(2 day M5), 25 day M5. These are the basic primary quantities. We may now regard the subarea mean values as point values. Now, for each of these 'points', proceed as follows.

Table 3.10 requires only the ratio $r$ = (60 minute M5)/(2 day M5) to give directly the values of M5 for all durations from 1 minute to 48 hours, as percentages of 2 day M5. Multiplying these percentages by the value of 2 day M5 gives M5 for durations 1 minute to 48 hours.

Then Table 3.2 requires only the value of AAR to give directly the values of 72 hour M5 and 96 hour M5 as percentages of 2 day M5. Multiply by 2 day M5 to obtain 72 hour M5 and 96 hour M5.

Linear interpolation between values for 96 hours and 25 days, on a diagram of log M5, log $D$, gives M5 for all durations between 96 hours and 25 days. We now have M5 values, that is values with return period 5 years, for each 'point', for any desired duration between 1 minute and 25 days.

We now need the same information on $MT$ values, that is values with return period $T$ years. Proceed as follows. It is shown in Chapter 2 that the rainfall for return period $T$ does not depend directly on duration $D$, but only on the value of M5. This value of M5 will be associated with a range of durations for different regions of the United Kingdom. Thus, given M5, there is a corresponding multiplier, $MT$/M5, called the 'growth factor' for the return period $T$, which gives $MT$ (the value with return period $T$) when M5 is multiplied by $MT$/M5.

A two-way table of growth factors $MT$/M5 for England and Wales is given as Table 2.7 for return periods 2, 10, 20, 50, 100, 1000, 10 000 years, and estimated maximum, and for values of M5 equal to 0.5, 2, 5, 10, 15, 20, 25, 30, 40, 50, 75, 100, 150, 200, 500, 1000 mm. (The maxima 2M and 1M which occur twice a year and once a year respectively in the partial duration series are also given.) They are also shown in Figure 2.4. Growth factors for Scotland and Northern Ireland are given in Table 2.9. Now, for a given point, and for all durations from 1 minute to 25 days we have the corresponding value of M5, and multiplying each of these by the appropriate value of $MT$/M5 for $T = 100$ we obtain M100, the 100 year return period values, for each of these durations. We do the same for all other return periods. The estimated maximum is similarly derived using Table 4.2 but this is only a provisional estimate. So we have for the given point a two-way table of rainfall values $R$ for durations between 1 minute and 25 days, and return period 2M, 1M, M2, M5, . . . M1000, etc., and the provisional estimated maximum.

We now compute the two-way table of $R$ values for each $D$ and $T$ for each representative 'point' of the catchment, and for each $D$, $T$ pair we mean these 'point' values to get a catchment mean value. If the subareas are not quite equal in size, a weighted mean of the 'point' values must be taken.

To obtain the *areal* rainfall value $R$ for the catchment, of area $A$, for the same $D$ and $T$, we multiply the mean point value of $R$ by the appropriate areal reduction factor (ARF) given in Table 5.2 (or Figure 5.1) of Chapter 5. Values of ARF are given for paired values of $D$ and $A$ for $D$ in the range 1 minute to 25 days and $A$ in the range 1–30 000 km$^2$. We now have the areal rainfall $R$ for the given catchment area $A$ and the required values of $D$ and $T$.

The time variation of point, and areal, rainfall for a storm of given duration can be described by a storm profile of rainfall intensity against time during the storm. Investigations briefly described in Chapter 6 show that the profile may be regarded as essentially symmetrical about the most intense part of the storm. Peaked profiles with very high intensities are typical of thunderstorms; and more flat profiles of frontal rainfall storms. The percentage frequency of storm profiles for point rainfalls, graded according to peak intensity, is given for summer and winter seasons in Chapter 6, Tables 6.2 and 6.3 respectively, and for areal rainfall for summer storms in Table 6.4. The median or some other more peaked or flat profile may be chosen to describe the time variation of rainfall throughout the storm. Profile intensities are given in units of mean storm intensity.

Estimates of maximum point rainfall for durations 2 hours and 24 hours are given in Figure 4.1 and 4.2. Given the AAR, Table 4.1 gives estimated maxima for durations less than 2 hours as a percentage of 2 hour maximum. Estimates of maximum point rainfall for durations between 2 and 24 hours are given by linear interpolation on an $R$, log $D$ diagram. Estimates of maximum point rainfall for 48, 72, 96 hour durations are given as percentages of 24 hour fall in Table 4.4. Estimates of maximum point fall for 25 days are taken as the provisional estimated maximum from the appropriate growth factors estimate.

Estimates of 192 hour maximum point fall are then obtained from Table 4.4 as a percentage of the 25 day fall; and maxima for intermediate durations are obtained by interpolation on an $R$, log $D$ diagram. Estimated maximum areal rainfalls are obtained by multiplying meaned point maxima for a catchment by the appropriate ARF. Estimates are sometimes required for maxima which are recorded within a given month, or a given season. These are discussed in Section 8.4.

## 8.2 Rainfall estimates for the Tyne catchment

### *8.2.1 Subdivision of the catchment*

The areas of the headwaters of the North Tyne and the South Tyne have AAR between 1000 and 2000 mm. The low-lying east of the catchment has AAR between 600 and 800 mm, and the central areas between these two have AAR between 800 and 1000 mm.

The essential parameters for rainfall estimates; AAR, 2 day M5, and the ratios of 60 minute M5 to 2 day M5 and 25 day M5 to AAR, were required for each region. Maps of these parameters are shown in Figures 8.1, 8.2, 8.3, and 8.4(a). These are sections of Figures 3.1, 3.2, 3.5 and 3.4 respectively, given here for ease of reference.

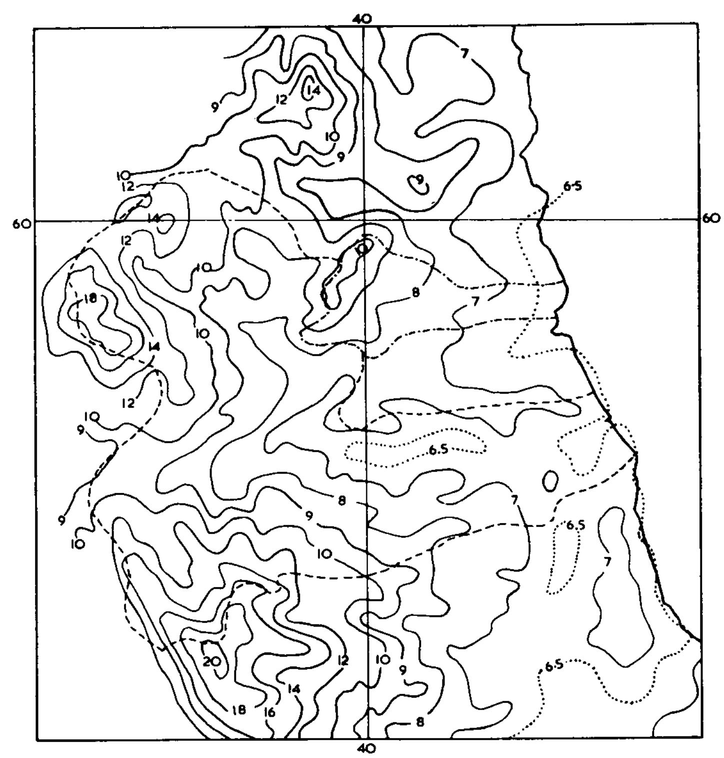



**Fig 8.1** Example catchments. Tyne (– – –) and Wansbeck (·–·–·) average annual rainfall 1941–70 (mm × 100).

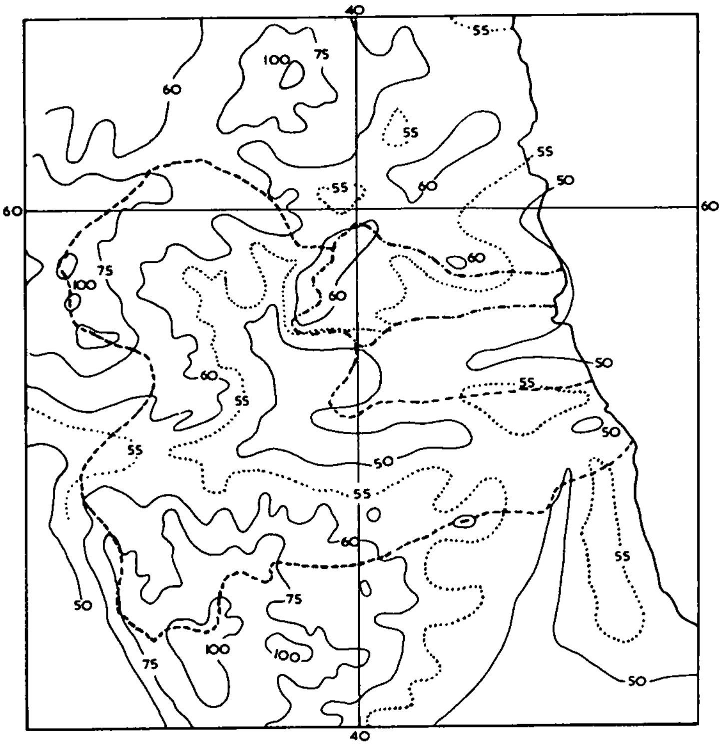



Fig 8.2 Example catchments. Tyne (– – –) and Wansbeck (·–·–·) 2 day M5 rainfall (mm).

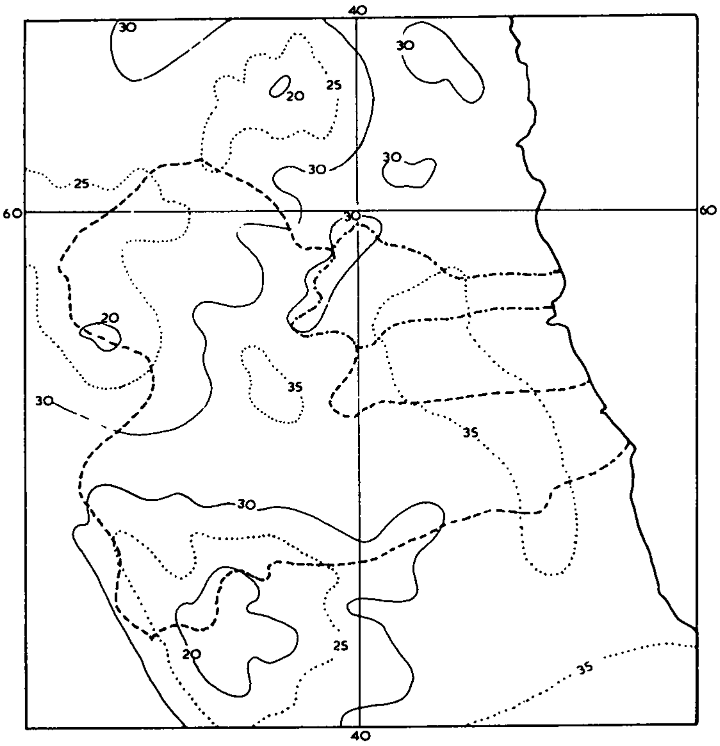



Fig 8.3 Example catchments. Tyne (– – –) and Wansbeck (·–·–·) percentage ratio of 60 minute M5 to 2 day M5.

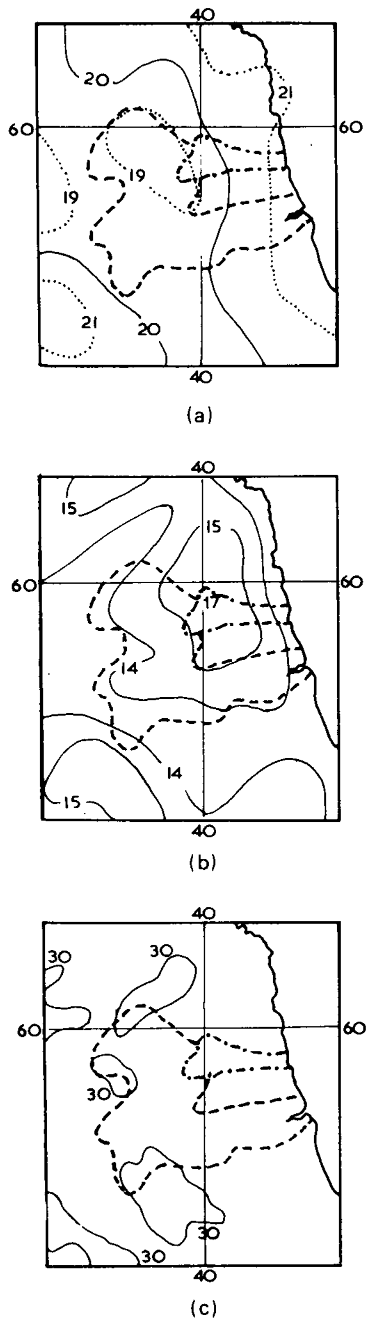



**Fig 8.4** Example catchments. Tyne (– – –) and Wansbeck (.–.–.).
*a* Percentage ratio of 25 day M5 to average annual rainfall; *b* estimated maximum 2 hour rainfall (mm × 10); *c* estimated maximum 24 hour rainfall (mm × 10).

### *8.2.2 Mean values of essential rainfall parameters*

The three regions were of almost equal area, and for simplicity they were marked out as three equal areas. An evenly spaced grid of points was placed over the catchment to give 20 grid points for each region. The means for each region are given in Table 8.1. The percentage ratios 2 day M5/AAR (Figure 3.3) were used as a check.

**Table 8.1** Meaned rainfall parameters for the Tyne catchment.

| Rainfall parameter | West | Centre | East |
|---|---|---|---|
| AAR (mm) | 1300 | 880 | 720 |
| 2 day M5 (mm) | 76 | 55 | 53 |
| 60 minute M5/2 day M5 (%) | 24 | 31 | 33 |
| 25 day M5/AAR (%) | 19.3 | 19.1 | 20.3 |
| 25 day M5 (mm) | 251 | 168 | 146 |
| 2 day M5/AAR (%) | 5.9 | 6.2 | 7.4 |

### *8.2.3 Derived rainfall estimates*

For the western region, the meaned percentage 25 day M5/AAR, 19.3%, and AAR 1300 mm, gives 25 day M5 = 0.193 × 1300 = 251 mm.

From Table 3.10† interpolating for the percentage ratio 60 minute M5/2 day M5 = 24, we obtain M5 for all durations from 1 minute to 48 hours as percentages of 2 day M5. In particular: M5 for 6 hours is 48.1% of 2 day M5 = 0.481 × 76 mm = 36.6 mm; M5 for 24 hours is 81.5% of 2 day M5 = 0.815 × 76 mm = 61.9 mm.

From Table 3.2, for the rainfall band 1000–1400 mm, M5 for 72 hours is 120% of 2 day M5 = 1.20 × 76 mm = 91.2 mm; M5 for 96 hours is 136% of 2 day M5 = 1.36 × 76 mm = 103.4 mm.

Other durations between 96 hours and 25 days are obtained by linear interpolation on an M5, log $D$ diagram; e.g. M5 for 192 hours = 144.5 mm. The M5 values for 6, 24, 72 and 192 hours are respectively 36.6, 61.9, 91.2 and 144.5 mm.

To get values for other return periods we use the growth factors M$T$/M5 of Table 2.7 and/or Figure 2.4. The interpolated values for $T$ = 100 and $T$ = 1000 are presented in Table 8.2, together with M2 for 24 hours.

**Table 8.2** Growth factors for the western Tyne.

| Duration (hours) | M5 (mm) | M$T$/M5 | | |
|---|---|---|---|---|
| | | $T = 2$ | $T = 100$ | $T = 1000$ |
| 6 | 36.6 | | 1.92 | 3.10 |
| 24 | 61.9 | 0.80 | 1.71 | 2.55 |
| 72 | 91.2 | | 1.55 | 2.17 |
| 192 | 144.5 | | 1.45 | 1.92 |

Example, M100 for 6 h = 36.6 × 1.92 mm = 70.3 mm.

A brief summary of derived data for the three regions of the Tyne is given in Table 8.3, obtained from the basic parameters of Table 8.1.

Since the areas of the three regions are equal, we can take as the catchment mean point rainfall the mean for the three regions, for each duration and return period. For each duration, we can find the areal reduction factor, ARF, corresponding to an area $A$ = 3000 km$^2$, from Table 5.2 and/or Figure 5.1; and hence convert catchment mean point rainfall amounts to catchment areal amounts by multiplying by the corresponding value of ARF. Table 8.4 gives the meaned point values, the corresponding ARF, and catchment areal rainfall amounts.

Strictly speaking, all the calculations which have been made on regional mean values of the essential rainfall parameters ought to have been made for each grid point of the catchment, but there is no loss of accuracy in using mean values for fairly homogeneous regions.

†Table 3.10 as printed has been rounded off.

| | West | Central | East |
|---|---|---|---|
| *a* Ratios (%) | | | |
| 6 h M5/2 day M5 | 48.1 | 55.5 | 57.4 |
| 24 h M5/2 day M5 | 81.5 | 85.5 | 86.5 |
| 72 h M5/2 day M5 | 120 | 119 | 117 |
| 96 h M5/2 day M5 | 136 | 133 | 129 |
| *b* Rainfall (mm) | | | |
| 6 h M5 | 36.6 | 30.5 | 30.4 |
| 24 h M5 | 61.9 | 47.0 | 45.8 |
| 72 h M5 | 91.2 | 65.5 | 62.0 |
| 96 h M5 | 103.4 | 73.2 | 68.4 |
| 192 h M5 | 144.5 | 100.0 | 91.0 |
| *c* Growth factors | | | |
| 6 h M100/M5 | 1.92 | 1.97 | 1.97 |
| M1000/M5 | 3.10 | 3.25 | 3.25 |
| 24 h M2/M5 | 0.80 | 0.79 | 0.79 |
| M100/M5 | 1.71 | 1.82 | 1.83 |
| M1000/M5 | 2.55 | 2.84 | 2.87 |
| 72 h M100/M5 | 1.55 | 1.69 | 1.71 |
| M1000/M5 | 2.17 | 2.48 | 2.54 |
| 192 h M100/M5 | 1.45 | 1.54 | 1.55 |
| M1000/M5 | 1.92 | 2.12 | 2.17 |
| *d* Rainfall (mm) | | | |
| 6 h M5 | 36.6 | 30.5 | 30.4 |
| M100 | 70.3 | 60.1 | 59.9 |
| M1000 | 113.5 | 99.1 | 98.8 |
| 24 h M2 | 49.5 | 37.1 | 36.2 |
| M5 | 61.9 | 47.0 | 45.8 |
| M100 | 105.8 | 85.5 | 83.8 |
| M1000 | 157.8 | 133.5 | 131.4 |
| 72 h M5 | 91.2 | 65.5 | 62.0 |
| M100 | 141.4 | 110.7 | 106.0 |
| M1000 | 197.9 | 162.4 | 157.5 |
| 192 h M5 | 144.5 | 100.0 | 91.0 |
| M100 | 209.5 | 154.0 | 141.1 |
| M1000 | 277.4 | 212.0 | 197.5 |

**Table 8.3** Derived rainfall data for the Tyne catchment.

| Duration (hours) | Meaned point rainfall (mm) | | | | ARF (%) | Catchment areal means (mm) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | M2 | M5 | M100 | M1000 | | M2 | M5 | M100 | M1000 |
| 6 | — | 32.4 | 63.2 | 103.5 | 79 | — | 25.6 | 49.9 | 81.8 |
| 24 | 40.9 | 51.1 | 91.2 | 140.3 | 86 | 35.1 | 43.9 | 78.4 | 120.7 |
| 72 | — | 71.8 | 118.3 | 171.4 | 90 | — | 64.6 | 106.5 | 154.3 |
| 192 | — | 109.4 | 165.6 | 226.5 | 92 | — | 100.6 | 152.4 | 208.4 |

**Table 8.4** Meaned point rainfall and areal mean rainfall for the Tyne catchment.

Example, the estimated catchment areal rainfall for 24 hours with return period 100 years is 78.4 mm.

### *8.2.4 Storm profiles for the Tyne catchment*

The 24 hour catchment M100 areal storm is 78.4 mm; with mean intensity 3.27 mm per hour. Let us apply this mean intensity to the median summer profile, given in Table 6.2. Table 8.5 gives the durations on either side of centre, obtained by multiplying the percentages in Table 6.2 by 24 hours, together with intensities.

It should be remembered that seasonal rainfall events (e.g. M5) can differ significantly from annual events (Table 3.9). On such occasions the seasonal storm profile should be applied to the appropriate seasonal

| Duration (hours) on either side of storm centre | | Proportion of mean intensity | Intensity (mm per hour) |
|---|---|---|---|
| Cumulative duration | Duration | | |
| 0–0.48 | 0.48 | 3.75 | 12.26 |
| 0.48–1.2 | 0.72 | 3.0 | 9.81 |
| 1.2 –2.4 | 1.2 | 2.1 | 6.87 |
| 2.4 –4.8 | 2.4 | 1.0 | 3.27 |
| 4.8 –7.2 | 2.4 | 0.6 | 1.96 |
| 7.2 –9.6 | 2.4 | 0.4 | 1.31 |
| 9.6 –12.0 | 2.4 | 0.3 | 0.98 |
| Mean intensity | | | 3.27 |

**Table 8.5** Median profile for the 24 hour 100 year storm for the Tyne catchment.

rainfall event, although in the Tyne example the annual and summer events are about the same.

The problem of computing the flood discharge of any desired return period is fully dealt with in Volume I; the choice of storm profile and the importance of antecedent conditions, storm duration, and of catchment characteristics, are discussed therein. However, an initial quick assessment of the 100 year flood discharge can be derived if the 2 year discharge is known. For example, from Table 8.4 the ratio of the 100 year and 2 year catchment areal means for 24 hours is 78.4 mm/35.1 mm = 2.23. The ratio for 36 hours is 2.18. This ratio may be applied to the 2 year flood discharge to give an initial quick estimate of the 100 year flood discharge.

## 8.3 Rainfall estimates for the Wansbeck catchment

### *8.3.1 Subdivision of the catchment*

The areas of the headwaters of the Font, Hart Burn, and Wansbeck have AAR between 850 and 1100 mm, and the eastern areas between 650 and 850 mm. See Figure 8.1. Calculations were made as in Section 8.2.

### *8.3.2 Mean values of essential rainfall parameters*

Two equal areas, west and east, were taken, and an evenly spaced grid of points placed over the catchment to give 10 grid points for each region. Table 8.6 gives meaned rainfall parameters for each region.

| Rainfall parameter | West | East |
|---|---|---|
| AAR (mm) | 930 | 710 |
| 2 day M5 (mm) | 60 | 53 |
| 60 minute M5/2 day M5 (%) | 29 | 33 |
| 25 day M5/AAR (%) | 19.3 | 20.7 |
| 25 day M5 (mm) | 179 | 147 |
| 2 day M5/AAR (%) | 6.4 | 7.5 |

**Table 8.6** Meaned rainfall parameters for the Wansbeck catchment.

### *8.3.3 Derived rainfall estimates*

For the western region, the mean 2 day M5 is 60 mm (a check is given from mean percentage 6.4 for 2 day M5/AAR and AAR 930 mm). The mean value of 60 minute M5/2 day M5 is 29%.

Using Table 3.10 and interpolating for the value 29%, we obtain the M5 values for durations less than 48 hours:

| Duration ($D$) | M5($D$)/M5(2 day) (%) | M5($D$) (mm) |
|---|---|---|
| 5 min | 9.9 | 5.9 |
| 30 min | 22.5 | 13.5 |
| 2 h | 36.9 | 22.1 |
| 6 h | 53.5 | 32.1 |
| 24 h | 84.4 | 50.6 |
| 48 h | 106 | 63.6 |

For any duration, say 30 minutes, with M5 = 13.5 mm, growth factors M$T$/M5 are obtained from Table 2.7 and/or Figure 2.4, e.g.

| Duration | M5 (mm) | 1M/M5 | M10/M5 | M100/M5 | Est. max. /M5 |
|---|---|---|---|---|---|
| 30 min | 13.5 | 0.62 | 1.22 | 1.96 | 7.2 |

1M = 8.4 mm M10 = 16.5 mm M100 · 26.5 mm Est. max. – 97.2 mm.

For each required duration, the values of M$T$ are obtained for both west and east. They are given in Table 8.7, together with the catchment means. Values of the areal reduction factor, ARF, are interpolated, for each duration and for an area of 350 km$^2$, from Figure 5.1. These values are also included in the table.

Table 8.7 Derived rainfall (mm) for the Wansbeck catchment.

| Duration | 1M | M2 | M5 | M10 | M100 | M1000 | Est. max. | ARF (%) |
|---|---|---|---|---|---|---|---|---|
| 5 min | | | | | | | | |
| West | 3.7 | 4.2 | 5.9 | 7.0 | 10.7 | 16.4 | 33.3 | |
| East | 3.8 | 4.5 | 6.2 | 7.3 | 11.3 | 17.5 | 35.3 | |
| Mean | 3.7 | 4.3 | 6.0 | 7.1 | 11.0 | 16.9 | 34.3 | 34 |
| 30 min | | | | | | | | |
| West | 8.4 | 9.5 | 13.5 | 16.5 | 26.5 | 42.6 | 97.2 | |
| East | 8.6 | 9.7 | 13.8 | 16.8 | 27.2 | 44.0 | 99.4 | |
| Mean | 8.5 | 9.6 | 13.6 | 16.6 | 26.8 | 43.1 | 98.3 | 60 |
| 2 h | | | | | | | | |
| West | 14.4 | 15.9 | 22.1 | 27.2 | 45.3 | 75.4 | 172.4 | |
| East | 14.2 | 15.7 | 21.8 | 26.8 | 44.7 | 74.6 | 170.0 | |
| Mean | 14.3 | 15.8 | 21.9 | 27.0 | 45.0 | 75.0 | 171.2 | 78 |
| 6 h | | | | | | | | |
| West | 21.8 | 24.1 | 32.1 | 38.5 | 62.6 | 101.8 | 224.7 | |
| East | 20.7 | 22.8 | 30.4 | 36.8 | 58.4 | 92.7 | 215.8 | |
| Mean | 21.2 | 23.4 | 31.2 | 37.6 | 60.5 | 97.2 | 220.2 | 86 |
| 24 h | | | | | | | | |
| West | 36.4 | 39.9 | 50.6 | 58.7 | 90.6 | 139.8 | 278.3 | |
| East | 32.5 | 35.7 | 45.8 | 53.6 | 84.3 | 132.6 | 267.9 | |
| Mean | 34.4 | 37.8 | 48.2 | 56.1 | 87.4 | 136.2 | 273.1 | 91 |
| 48 h | | | | | | | | |
| West | 47.1 | 50.9 | 63.6 | 73.1 | 108.1 | 159.9 | 292.6 | |
| East | 41.0 | 44.4 | 56.2 | 64.6 | 98.4 | 149.9 | 283.8 | |
| Mean | 44.0 | 47.6 | 59.9 | 68.8 | 103.2 | 154.9 | 288.2 | 93 |

The catchment areal means are given in Table 8.8.

Let us consider rainfall of 8 hours duration as an example. From Table 8.8 the ratio of 1000 year to 2 year 6 hour rainfall is 83.6 mm/20.1 mm = 4.16, and the corresponding ratio for 8 hours is 4.05. This ratio may be applied to the 2 year flood discharge to give a rough estimate of the 1000 year flood discharge, neglecting the effects of antecedent conditions, etc.

| Return period | Duration | | | | | |
|---|---|---|---|---|---|---|
| | 5 min | 30 min | 2 h | 6 h | 24 h | 48 h |
| 1M | 1.3 | 5.1 | 11.2 | 18.2 | 31.3 | 40.9 |
| M2 | 1.5 | 5.8 | 12.3 | 20.1 | 34.4 | 44.3 |
| M5 | 2.0 | 8.2 | 17.1 | 26.8 | 43.9 | 55.7 |
| M10 | 2.4 | 10.0 | 21.1 | 32.3 | 51.1 | 64.0 |
| M100 | 3.7 | 16.1 | 35.1 | 52.0 | 79.5 | 96.0 |
| M1000 | 5.7 | 25.9 | 58.5 | 83.6 | 123.8 | 144.0 |
| Est. max. | 11.7 | 59.0 | 133.5 | 189.4 | 248.5 | 268.0 |

**Table 8.8** Areal mean rainfall (mm) for the Wansbeck catchment.

The 1000 year catchment fall for 8 hours is found to be 90.7 mm, with mean intensity 11.34 mm per hour. The 75 percentile summer profile for this storm is given in Table 8.9.

| Duration (minutes) on either side of storm centre | | Proportion of mean intensity | Intensity (mm per hour) |
|---|---|---|---|
| Cumulative duration | Duration | | |
| 0–9.6 | 9.6 | 6.0 | 68.04 |
| 9.6–24 | 14.4 | 4.0 | 45.36 |
| 24–48 | 24 | 2.1 | 23.81 |
| 48–96 | 48 | 0.65 | 7.37 |
| 96–144 | 48 | 0.4 | 4.54 |
| 144–180 | 48 | 0.3 | 3.40 |
| 180–240 | 48 | 0.2 | 2.27 |
| Mean intensity | | | 11.34 |

**Table 8.9** 75 percentile storm profile for the 8 hour 1000 year catchment storm, for the Wansbeck catchment.

### *8.3.4 Estimates of maximum rainfall*

The growth curve estimates of maximum point rainfall for 2 hours and 24 hours (Table 8.7) are 171 and 273 mm respectively, in quite good agreement with Figures 8.4(b) and 8.4(c). (Those are sections of Figures 4.1 and 4.2.) We might take 160 mm and 275 mm from these maps of estimated maxima.

Table 4.1 gives an estimate for the 5 minute maximum, 23% of the 2 hour maximum; and for the 30 minute maximum, 65% of the 2 hour maximum, *viz.* 5 minute maximum $= 0.23 \times 160$ mm $= 36.8$ mm, 30 minute maximum $= 0.65 \times 160$ mm $= 104$ mm.

These values are in quite good agreement with the estimates of maxima using the envelope of the growth curves and as presented in Table 4.2, i.e. 34.3 and 98.3 mm respectively.

Following 4.3.3, interpolation on a log linear diagram gives estimates of maxima for durations between 2 and 24 hours, using data of maxima for 2 hours, 160 mm; and 24 hours, 275 mm. This gives an estimate of 203 mm for the 6 hour maximum.

From Table 4.4, the estimated 48 hour maximum is 110% of the 24 hour maximum, i.e. 48 hour maximum $= 1.10 \times 275 = 302$ mm. The agreement with the growth curve point maxima, Table 8.7, is good.

Applying the values of ARF from Table 8.7 to our meaned point maxima, we obtain the catchment areal maxima, *viz.* 5 minutes, 12.5 mm; 30 minutes, 62 mm; 2 hours, 125 mm; 6 hours, 175 mm; 48 hours, 281 mm.

These are in very good agreement with the estimated maxima, obtained from the growth curve envelope, given in Table 8.8.

## 8.4 Monthly and seasonal variation of rainfall amounts

As an example of the variation, if we consider M5 values for duration 24 hours, we find from Table 3.9, for AAR in the three regions of the Tyne catchment, east 720 mm, centre 880 mm, west 1300 mm, the values of monthly and seasonal M5 as percentages of the corresponding M5 for annual maxima.

If we consider the eastern region, AAR 720 mm, then M5 percentages, using 1 day values from Table 3.9, are:

| Months | | | | | | | | | | | | Seasons | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan. | Feb. | Mar. | April | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. | Sum. | Win. |
| 45 | 39 | 39 | 38 | 48 | 50 | 63 | 65 | 56 | 56 | 53 | 46 | 96 | 70 |

To obtain the M100 values, as percentages of the corresponding M100 for annual maxima, we use Table 2.10 and 2.11. For example, the M5 value of 45% for January, a winter month, corresponds (by interpolation) to an M100 value of 47%; the M5 value of 63% for July, a summer month, corresponds (by interpolation) to an M100 value of 76%. The M5 value of 96% for the summer season corresponds to an M100 value of 98%; the M5 value of 70% for the winter season corresponds to an M100 value of 63%.

It is adequate to take the mean of the regional percentages, for a given month or season, as the catchment percentages of annual. The monthly and seasonal M5 and corresponding M100 percentages of annual are given in Table 8.10, together with the catchment mean values (using Tables 2.10 and 2.11).

**Table 8.10** Monthly and seasonal M5 and M100 percentages of annual for the regions of the Tyne catchment, for duration 24 hours, with mean percentages.

| Return period | Jan. | Feb. | Mar. | April | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. | Sum. | Win. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| East | | | | | | | | | | | | | | |
| M5 | 45 | 39 | 39 | 38 | 48 | 50 | 63 | 65 | 56 | 56 | 53 | 46 | 96 | 70 |
| M100 | 47 | 39 | 39 | 38 | 57 | 60 | 76 | 79 | 68 | 68 | 58 | 48 | 98 | 63 |
| Centre | | | | | | | | | | | | | | |
| M5 | 51 | 44 | 42 | 40 | 47 | 49 | 61 | 64 | 58 | 62 | 58 | 54 | 94 | 76 |
| M100 | 55 | 46 | 43 | 40 | 56 | 59 | 74 | 77 | 70 | 75 | 65 | 60 | 98 | 72 |
| West | | | | | | | | | | | | | | |
| M5 | 57 | 50 | 46 | 44 | 47 | 51 | 61 | 64 | 63 | 66 | 64 | 59 | 92 | 83 |
| M100 | 64 | 54 | 48 | 46 | 56 | 61 | 74 | 77 | 76 | 80 | 73 | 67 | 97 | 81 |
| Mean | | | | | | | | | | | | | | |
| M5 | 52 | 44 | 42 | 41 | 47 | 50 | 62 | 64 | 59 | 61 | 58 | 53 | 94 | 76 |
| M100 | 55 | 56 | 43 | 41 | 56 | 60 | 75 | 78 | 71 | 74 | 65 | 58 | 98 | 72 |

If now the mean percentages are applied to the respective catchment areal values of M5 and M100, we obtain estimates of the monthly and seasonal catchment areal values of M5 and M100. For example, Table 8.4 gave the 24 hour meaned point values, the areal reduction factor ARF, and catchment areal means, *viz.* M5 51.1 mm, 86%, 43.9 mm; M100 91.2 mm, 86%, 78.4 mm. The mean percentages for the catchment for January are 52 and 55 for M5 and M100 respectively, giving catchment areal estimates for January M5 $= 0.52 \times 43.9$ mm $= 23$ mm; M100 $= 0.55 \times 78.4$ mm $= 43$ mm.

Table 8.11 gives the monthly and seasonal values of M5 and M100 for the Tyne catchment, for duration 24 hours.

**Table 8.11** Monthly, seasonal and annual values of M5 and M100 areal rainfall (mm) for the Tyne catchment, for duration 24 hours.

| Return period | Jan. | Feb. | Mar. | April | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. | Sum. | Win. | Ann. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| M5 | 23 | 19 | 18 | 18 | 21 | 22 | 27 | 28 | 26 | 27 | 25 | 23 | 41 | 33 | 44 |
| M100 | 43 | 44 | 34 | 32 | 44 | 47 | 59 | 61 | 56 | 58 | 51 | 45 | 77 | 56 | 78 |

It will be noticed that these estimates have essentially used the annual ARF, 86%, for estimating monthly and seasonal areal falls. In Chapter 5, no reference was made to estimation of monthly and seasonal values of ARF, since no extensive work was carried out. But for several Northumbrian catchments the 2 day maximum areal falls for each month, season and year were evaluated for long periods of record, and monthly, seasonal and annual values of M5 and M100 areal rainfall estimated. These were in excellent agreement with values obtained by the methods outlined in this chapter. Thus, the implicit assumption of constancy of ARF throughout the year has been justified. It would moreover seem reasonable for all catchments that, for those durations of practical importance, i.e. those for which the (annual) value of ARF is high, it would be appropriate to use the same value of ARF throughout the year.

The M5 and M100 values in Table 8.11 may be used to interpolate other return periods, using linear interpolation on a log $x$, $y$ diagram; and, with caution, for extrapolation to higher return periods.

# 9 Some historic heavy rainfall events

## 9.1 Summary

Brief accounts are presented of several of the more extreme rainfall events in the United Kingdom during this century for which there are authentic details.

For each rainfall event a map of the rainfall is presented with a brief summary of associated weather developments and, whenever possible, information on the size of area affected and the time profile of the rainfall event.

The 10 events have been chosen from the largest recorded in the United Kingdom this century to represent different types and durations of storm and the different parts of the United Kingdom affected. The storms are presented in order of duration, starting with the shortest, for which no rainfall map is given.

## 9.2 The storm of 11 July 1932 Cranwell, Lincs. (126 mm in 2 hours)

Severe thunderstorms occurred at many places in the north of England on the afternoon of 11 July. Daily rainfall totals were as large as 135 mm at Barnoldswick in the Pennines and 130 mm at Cranwell, near Sleaford, Lincs. (Meterorological Office, 1932). Low pressure over France gave slack pressure gradients over England with light south east winds. After morning sunshine the temperature had risen to 29°C (85°F) at Cranwell before the thunderstorm finally broke at 1600 hours.

A recording raingauge was in operation there and Figure 9.1 shows the rainfall trace between 1600 and 1900 hours when the whole day's fall of 130 mm was recorded. From the original chart the following estimates were made of the largest amounts of rainfall in the specified times: 31.7, 49.8, 63.8, 74.4, 106, and 126 mm in 15, 30, 45, 60, 90 and 120 minutes respectively.

Comparable falls have occurred several times. For instance 118 mm of rain fell in less than 2½ hours in an afternoon thunderstorm at Kensington on 16 June 1917, 130 mm in about 2 hours in evening thunderstorms at Knockholt, near Sevenoaks, Kent on 5 September 1958, and 111 mm in 2 hours in an afternoon thunderstorm at Miserden, near Gloucester, on 10 June 1970.

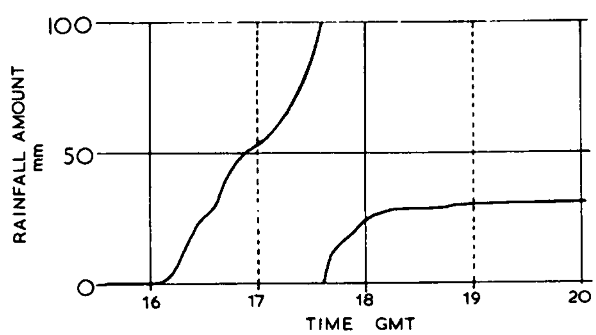



**Fig 9.1** Rainfall profile at Cranwell, Lincs., 11 July 1932.

## 9.3 The storm of 8 June 1957 Camelford, Cornwall (at least 138 mm in 2½ hours)

Widespread thunderstorms occurred in the West Country in a showery south westerly airstream associated with a slow moving depression off southern Ireland. Temperatures were only around 17°C (63°F) inland. Thunderstorms were especially severe at Camelford during the afternoon, and the day's total rain was 180 mm at Camelford, Roughtor View, and 161 mm at Camelford, Advent.

Very severe hail also occurred in the storm and it was estimated (Bleasdale, 1957) that much of the hail bounced out of the gauge during the heaviest part of the storm. The observer, Mr D. W. Bogle, estimated that the loss of catch must have been nearly 25 mm, and that 100 mm of rain and hail fell in the first hour of the storm. The isohyets drawn for 8 June are given in Figure 9.3, while Figure 9.2 gives the estimated rainfall profile at Mr Bogle's raingauge.

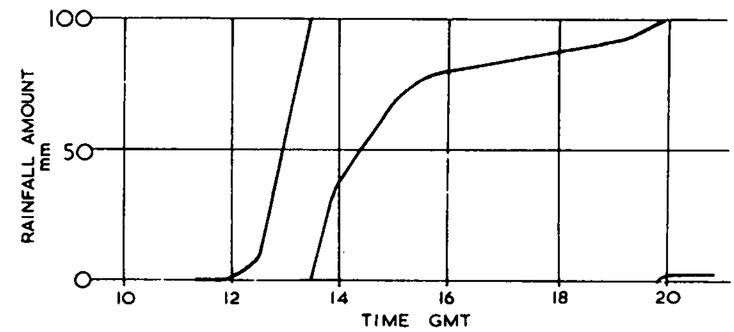



Fig 9.2 Estimated rainfall profile at Camelford, Cornwall, 8 June 1957.

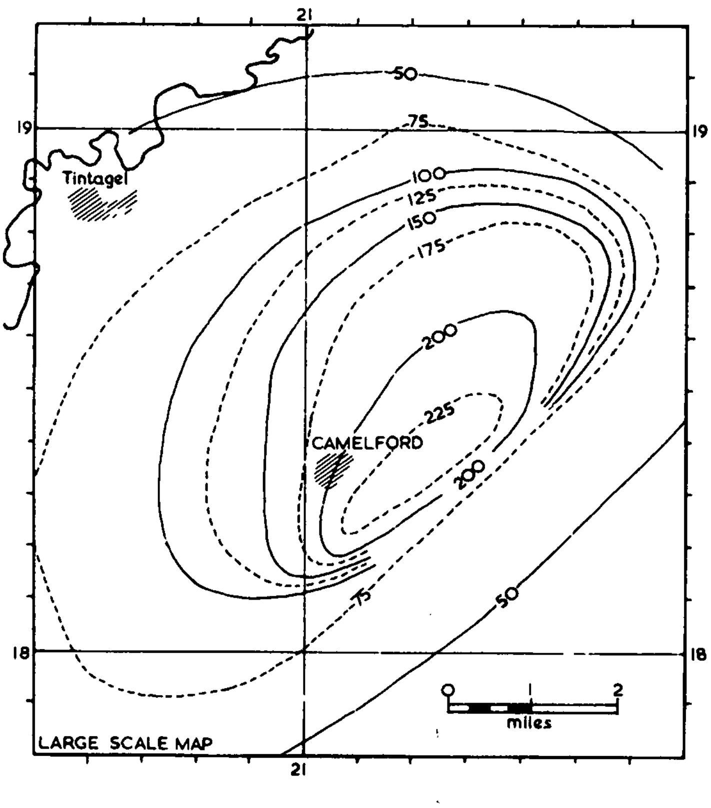



Fig 9.3 24 hour rainfall (mm) at Camelford, Cornwall, 8 June 1957, based on a map by C. H. Archer.

### 9.4 The storm of 4 August 1938 Torquay region, Devon (152 mm in 5 hours)

A shallow low pressure area off south west England brought warm air to Devon on 3 and 4 August with light easterly winds. Temperatures reached 25°C (77°F) at Torquay on the 3 August, falling only to 15°C (59°F) in the night. During the early morning of 4 August thunderstorms broke out widely over Devon, and gave particularly heavy falls in the Torquay region. At Stoke Gabriel (4 miles south west of Paignton) 152 mm of rain fell in 5 hours, at Bovey Tracey (15 miles north west of Torquay) 149 mm fell in 3¾ hours (Meteorological Office, 1938; Douglas, 1938). At Torquay, where 145 mm fell in just over 5 hours, the meteorological station had a recording gauge in operation, and the rainfall trace is shown in Figure 9.4. The isohyets for the combined rainfall days of 3 and 4 August are shown in Figure 9.5.

Similar falls occurred at Costessey, near Norwich, on the morning of 1 August 1972, when 138 mm of rain fell in less than 4 hours; at Portland, Dorset on the morning of 21 October 1908, when almost 175 mm fell in 5 hours (Green, 1908); and at Horncastle, Lincs. on the afternoon of 7 October 1960, when 184 mm fell in 6 hours.

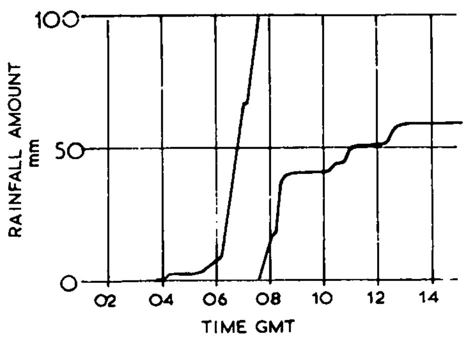



Fig 9.4 Rainfall profile at Torquay, 4 August 1938.

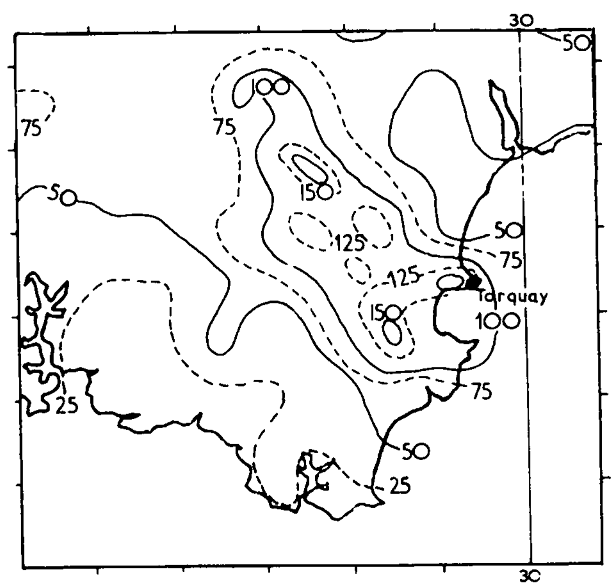


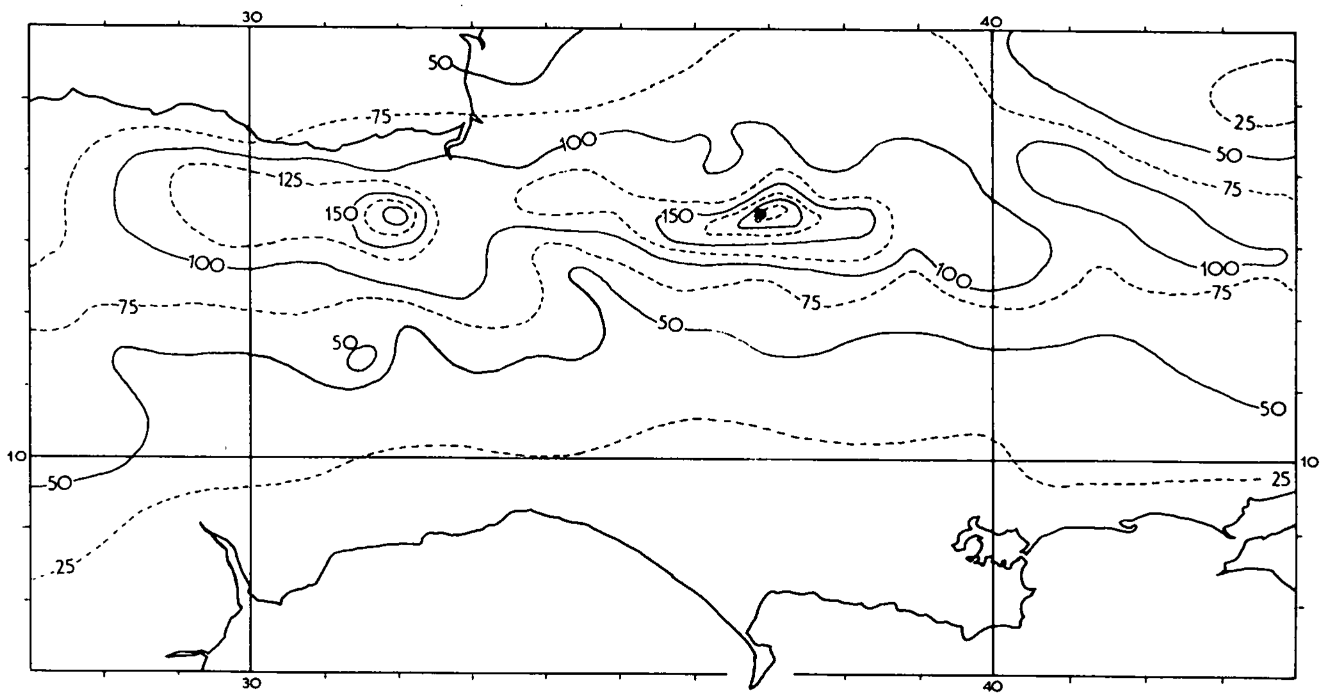

Fig 9.5 48 hour rainfall (mm) over Devon, 3–4 August 1938.

## 9.5 The storm of 28 June 1917 Bruton region, Somerset (200 mm in about 8 hours)

Pressure was low south east of the British Isles with northerly winds blowing over much of the country. A shallow depression moved quite quickly up the English Channel, crossing the Cherbourg peninsula during the afternoon and reaching Kent in the early morning of 29 June, when it turned south eastwards. In Somerset, a fine afternoon had followed some showers in the morning. Heavy rain began between 1730 and 1800 hours, increased in intensity as the evening went on, and came to a climax between 2300 hours on 28 June and 0100 hours on 29 June (Mill & Salter, 1917). Some thunder occurred during the long night rain, but it does not appear to have been a prominent feature.

Total rain for the rainfall day was 243 mm at Sexey's School, Bruton, 215 mm at King's School, Bruton, and 213 mm at Aisholt, Somerset. Figure 9.6 shows the isohyets for the rainfall event, while Figure 9.7 gives a representation of the time profile of the storm as reconstructed from evidence in 1917. From the original rainfall map it was estimated that 36 $km^2$ had more than 200 mm of rain, 240 $km^2$ more than 150 mm, and 2100 $km^2$ more than 100 mm.

Fig 9.6 24 hour rainfall (mm) over Somerset and Wiltshire, 28 June 1917. ●, Bruton.



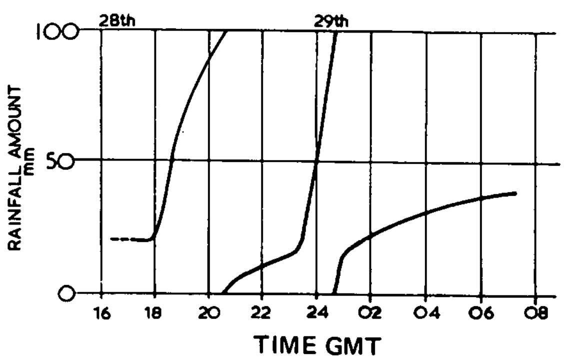




Fig 9.7 Estimated rainfall profile at Bruton, Somerset, 28–29 June 1917.

## 9.6 The storm of 18 July 1955 Weymouth region, Dorset (280 mm in about 15 hours)

A shallow low pressure area lay to the south east of the British Isles with light north easterly winds over south England and maximum temperatures around 21°C (70°F). A compact area of rain travelled slowly north eastwards across the English Channel, became stationary over Dorset and intensified to give two very heavy periods of rain before slowly moving back over the sea south westwards as it decayed (Meteorological Office, 1955). The total rain measurement of 280 mm in the rainfall day of 18 July at Martinstown, 3 miles south west of Dorchester, has never been exceeded in the United Kingdom, and is substantiated by nearby stations with 241 and 229 mm near Upwey. Figure 9.9 shows the isohyets for the storm, which can be seen to be unusually concentric for such storms.

In the central area of heavy rain it seems that the heavy rain began in the afternoon and continued well into the evening. There was a lull during the evening, and after that there was more heavy rain, continuing until about midnight before giving way to moderate and light rain in the early hours. About two thirds of the total amount fell before the evening lull. At Martinstown, 190 mm was recorded between 1430 and 1900 hours (approx.) and at Upwey, 166 mm by about 2030 hours. 114 mm was

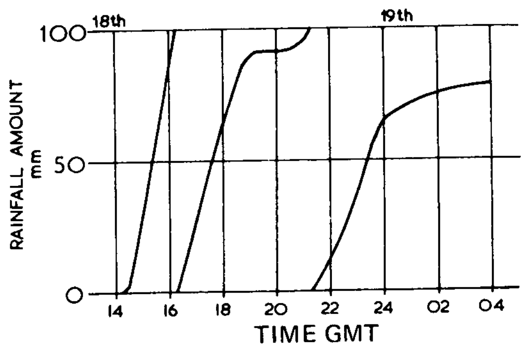



Fig 9.8 Estimated rainfall profile at Martinstown, Dorset, 18–19 July 1955.

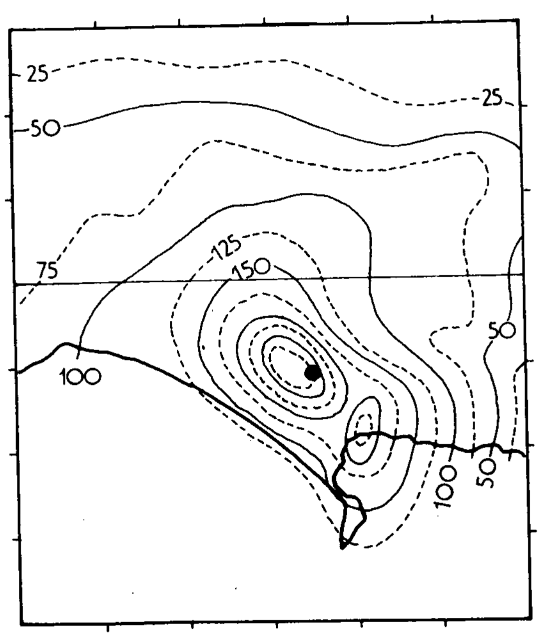



Fig 9.9 24 hour rainfall (mm) over Dorset, 18 July 1955. ●, Martinstown.

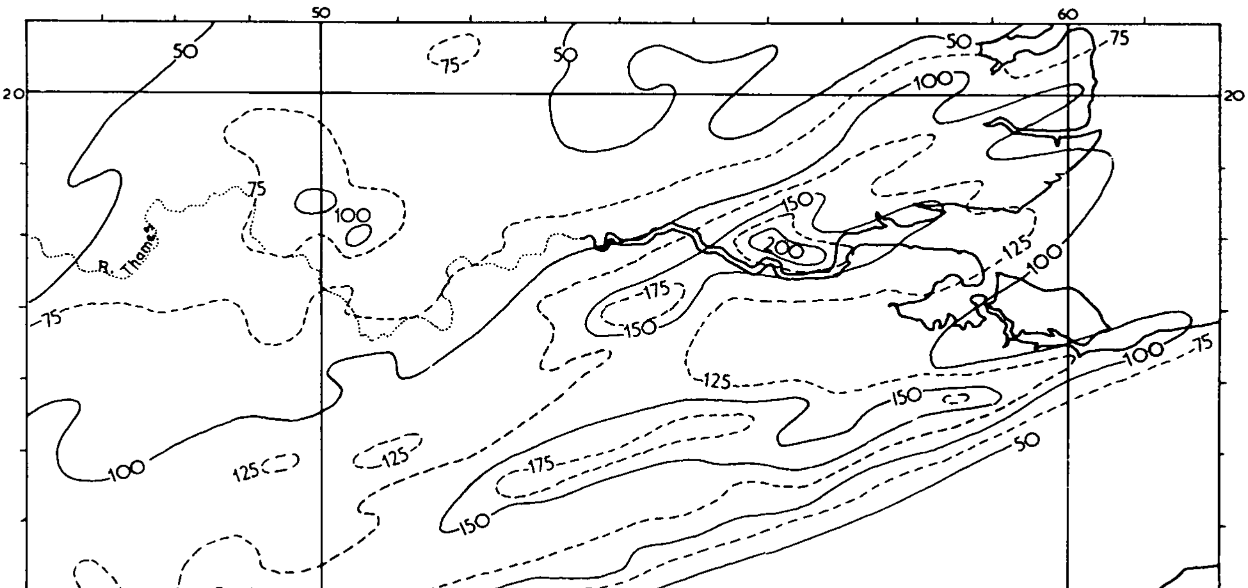
recorded in 2¾ hours at Litton Cheney, near Bridport. Figure 9.8 shows the rainfall profile at Martinstown as suggested by accounts of the rain.

The areas covered by the storm were 40 $km^2$ with more than 250 mm, 135 $km^2$ with more than 200 mm, 380 $km^2$ with more than 150 mm and 870 $km^2$ with more than 100 mm of rain.

## 9.7 The storm of 15 September 1968 south east England (190 mm in about 20 hours)†

A depression moved slowly over the Bay of Biscay, while a trough north eastwards to south east England intensified. Over much of south east England the winds were cold and cloudy from the north east. Outbreaks of heavy rain and thunderstorms on the afternoon of 14 September mostly died out by midnight. However, in the early morning of 15 September vigorous thunderstorms started to break out widely south of London, and showed little sign of movement during the morning. Much of the heaviest rain fell in this period. By midday the rain was generally less intense, but storms developed further north and there were renewed heavy storms during the evening in places affected by the morning storms.

Fig 9.10 48 hour rainfall (mm) over south east England, 14–15 September 1968.



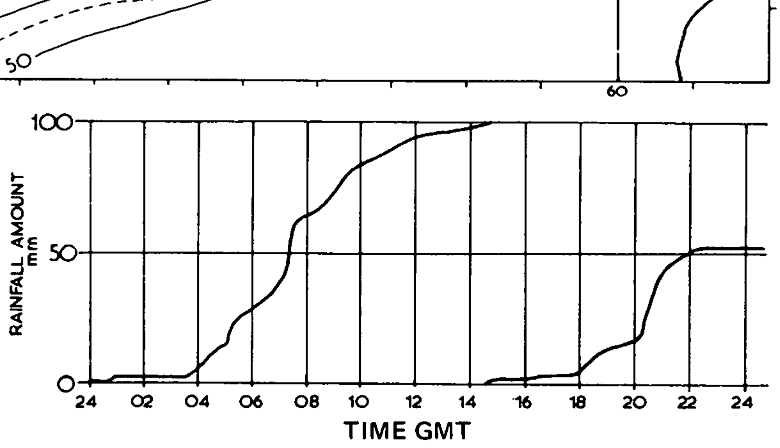




Fig 9.11 Rainfall profile at Fernhurst Sussex, 15 September 1968.

†A detailed case study is given by Salter & Richards (1974).

The heaviest rainfall in most places spanned the daily rainfall measurement at 0900 hours on 15 September (Meteorological Office, 1968b), so that Figure 9.10 shows the isohyets for the two rainfall days 14 and 15 September combined. Heaviest total falls over the 2 days were 201 mm at Marsh Farm S. Wks. and Stifford P. Sta. both near Grays Thurrock, Essex, 191 mm at Bromley and 190 mm at Godstone, Surrey. Figure 9.11 shows the time profile of the rain at Fernhurst, Sussex, where 162 mm fell: many recording gauges in operation at the start of the storm were flooded.

There were 16 $km^2$ with more than 200 mm, 660 $km^2$ with more than 150 mm, and 6500 $km^2$ with more than 100 mm of rain.

### 9.8 The storm of 26 August 1912 Norfolk (210 mm in 24 hours)

A small but well developed depression centred off the east coast of Kent at 0700 hours on 26 August moved slowly northwards to a position north east of Cromer, Norfolk at 1800 hours, where it turned eastwards (Mill & Slater, 1912). Rain began over Norfolk in the early hours of 26 August and continued in most places until about midnight. Figure 9.12 was reconstructed from reports and readings made at Norwich where 187 mm of rain fell, and shows the time profile of the rain during the civil day. The largest falls recorded over the 2 rainfall days 25 and 26 August were near Norwich where Sprowston Council School measured 210 mm and Brundall 205 mm. A total of about 40 rainfall stations recorded more than 150 mm in the 2 days. The isohyets of the storm are shown in Figure 9.13.

There were some 70 $km^2$ with more than 200 mm of rain, 1900 $km^2$ with more than 150 mm and 5000 $km^2$ with more than 100 mm. The floodmarks in Norwich, which go back over 300 years, show that the 1912 flood was 15 inches higher than the previous highest flood in 1614.

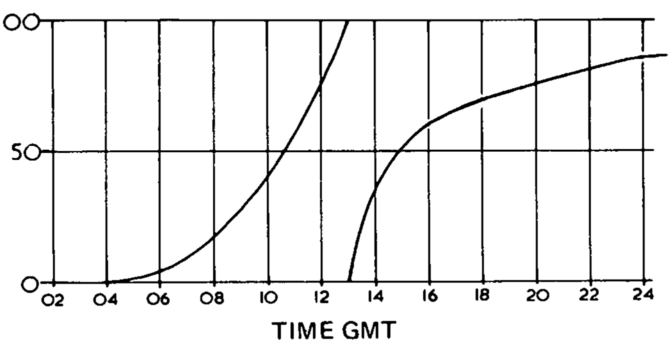



**Fig 9.12** Estimated rainfall profile at Norwich, 26 August 1912.

### 9.9 The storm of 25/26 September 1915 Inverness region (201 mm in about 40 hours)

A shallow depression moved slowly north to a point about 50 miles east of Peterhead, Aberdeen, by 0700 hours on 26 September. From this point the depression turned sharply to the east (Mill & Salter, 1915). Heaviest rainfall on the rainfall day of 25 September was 179 mm at Dalcross Castle, Croy, while 201 mm fell over the 2 rainfall days. Figure 9.14 shows

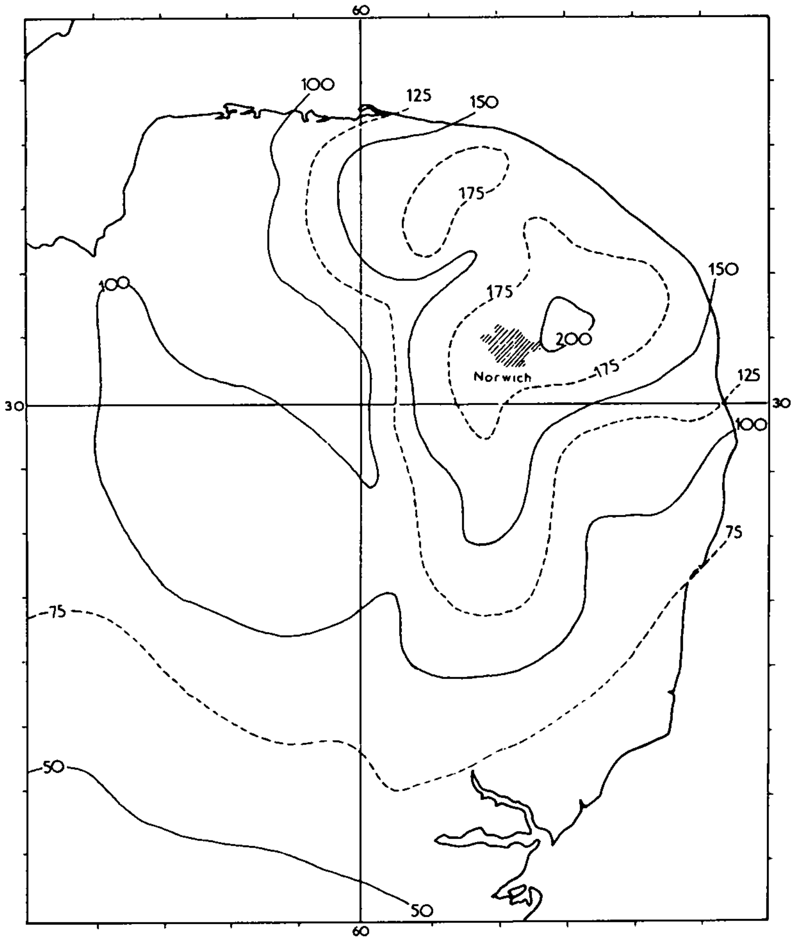



Fig 9.13 48 hour rainfall (mm) over East Anglia, 25–26 August 1912.

the isohyets for 25 and 26 September. At a rough estimate the duration of the storm was about 40 hours.

62 km$^2$ had more than 175 mm, 200 km$^2$ more than 150 mm and 1250 km$^2$ more than 100 mm of rain.

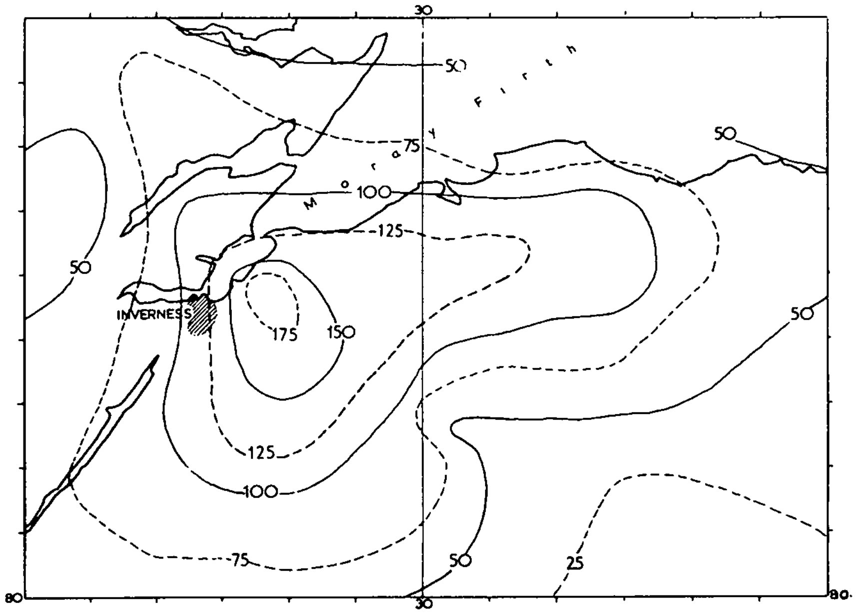



Fig 9.14 48 hour rainfall (mm) over north east Scotland, 25–26 September 1915.

## 9.10 The storm of 2/3 November 1931 west Britain (up to 244 mm in 2 days)

A large anticyclone lay to the south east of the British Isles while a complex depression was to the north west of Ireland and Scotland. A broad, strong south westerly airstream brought unusually warm and moist air across the western half of the British Isles with temperatures around 14°C (57°F). Strong winds and heavy rains affected all mountainous parts of the British Isles, with falls over the 2 rainfall days as large as 244 mm near Trecastle, south Wales, 219 mm at Patterdale, Westmorland, and 184 mm on Snowdon, north Wales (Meteorological Office, 1931). Figure 9.15 shows the isohyets over the country for the 2 rainfall days combined; Figure 9.16 shows the time profile of the rain at Princetown, Devon (Glasspoole, 1931).

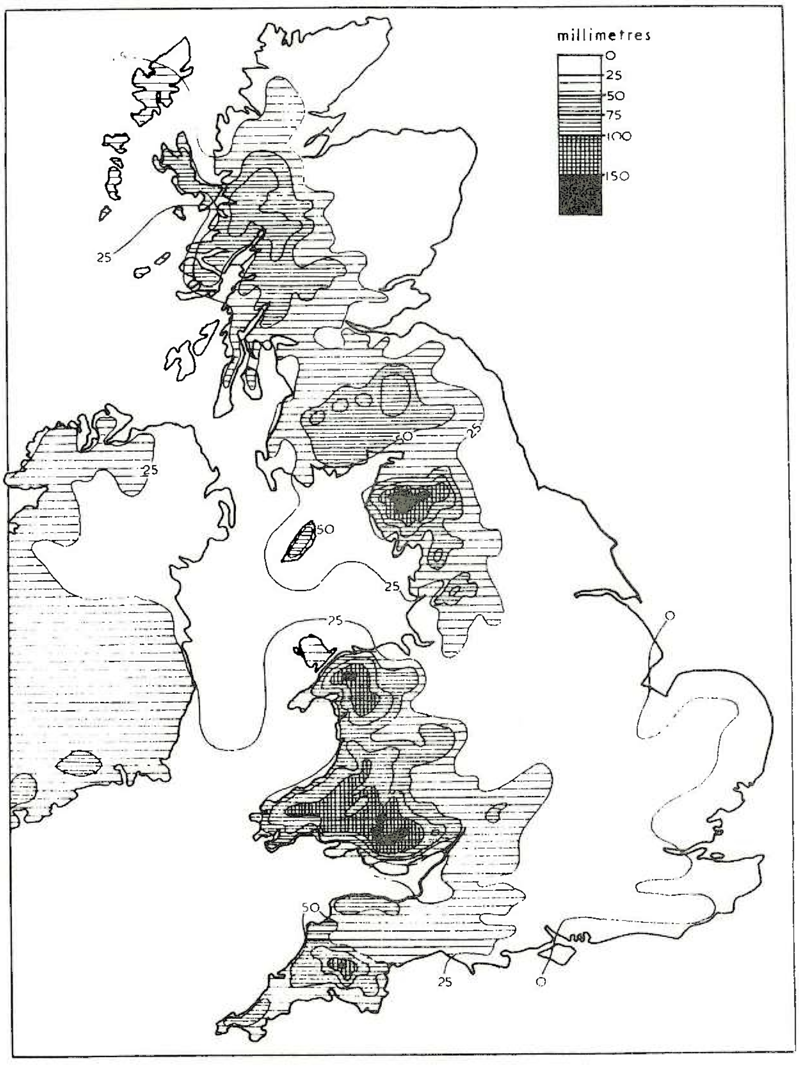



Fig 9.15 48 hour rainfall (mm) over British Isles, 2–3 November 1931 (a simplified map).

This rainfall event was not particularly outstanding, except in its wide extent from north to south. Many rainfall events in the mountainous parts of western Britain have produced similar falls; a more recent example occurred in west Scotland on 26 and 27 March 1968 with 252 mm at Kinlochewe, Ross and Cromarty. Considerably larger rainfall totals over

2 days have occurred many times at some of the wettest stations in the United Kingdom.

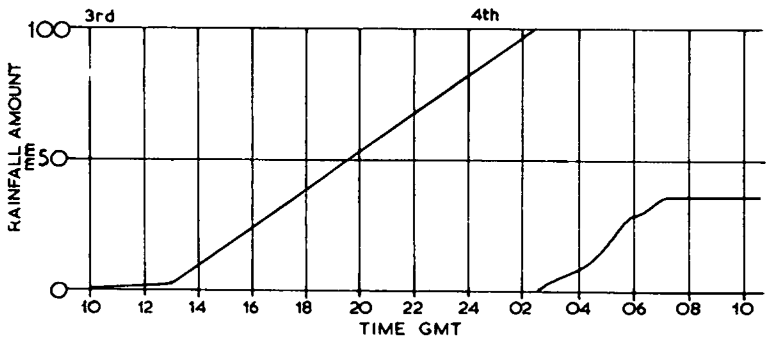



**Fig 9.16** Rainfall profile at Princetown, Devon, 3–4 November 1931.

## 9.11 The storm of 20–23 July 1930 North Yorkshire Moors (304 mm in 4 days)

A depression persisted off the east coast of England for most of this period 20–23 July, maintaining strong northerly winds over the North Yorkshire Moors. The distribution of rainfall was controlled to a large extent by the topography, the largest amounts occurring over the higher parts of the moors. The rain began at about 1500 hours on 20 July at Castleton, north Yorkshire, and continued almost without a break until 1200 hours on 23 July. The observers commented on the steadiness of the rain and the absence of intense falls (Meteorological Office, 1930). The largest rainfall total for the 4 days was 304 mm at Castleton, of which 68, 59, 145 and 32 mm fell on the four consecutive rainfall days 20–23 July. Figure 9.17 shows the isohyets for the 4 day period.

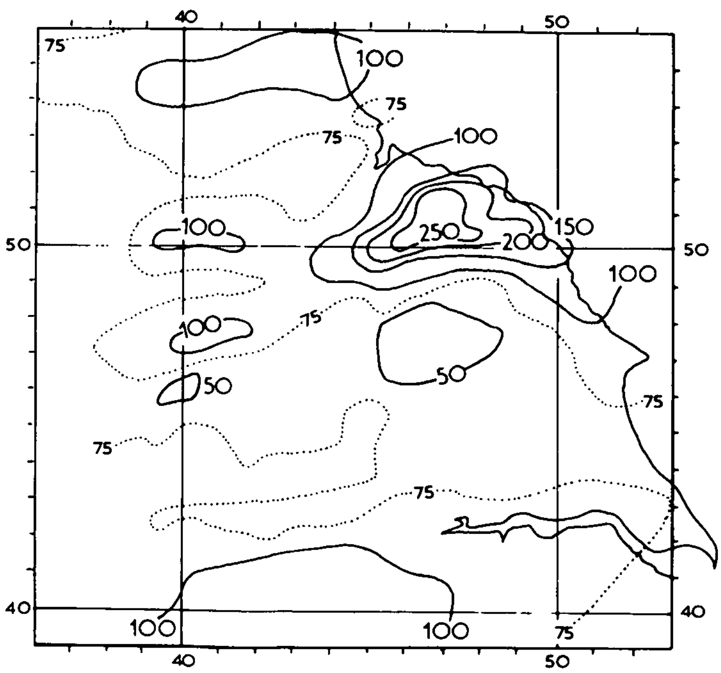



**Fig 9.17** 4 day rainfall (mm) over Yorkshire, 20–23 July 1930.

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