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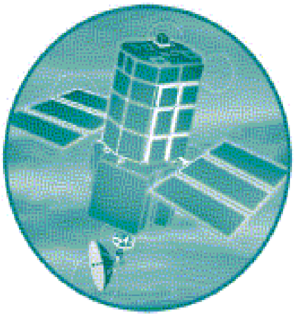

Extreme Rainfall and Flood Event Recognition

R&D Technical Report: FD2201

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Extreme Rainfall and Flood Event Recognition

R&D Technical Report FD2201
August 2002

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Statement of use

This document describes initial research undertaken to identify methods by which extreme rainfall and flood events might be recognized in order to provide improved flood warning and operational response. The document contains useful reference material on historical extreme rainfall events and Training Data sets, which may be of use to Defra and Environment Agency staff, research contractors and external agencies. Further work is required to test and develop the identified methods of extreme event recognition, and assessment of catchment susceptibility to such events, if they are to be implemented.

- Keywords – research; floods; warning; extreme; rainfall; training; recognition; response; susceptibility
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EXECUTIVE SUMMARY

Background - The most extreme hydrometeorological events that are likely to be experienced in the United Kingdom have received only limited study from the point of view of underlying consistency and predictability. Practically all such rainfall and flood events that have occurred in the last 100 years or so have been described, and in some cases have been analysed in order to seek their causes. However, guidance to flood forecasters to help identify these events remains skeletal. It is vital that signals of the possibility of such events be recognized as early as possible, preferably 24 hours or more in advance.

Main Objectives – The aim of the research was to investigate the nature of very extreme rainfall events and the meteorological situations leading to their occurrence, and also the susceptibility of river catchments to their spatial and temporal rainfall patterns. Given that such events are likely to have return periods of many thousands of years, the implications of the analysis for estimates of Probable Maximum Precipitation have also been considered. A subsidiary requirement of this work was to derive training data sets for some extreme events which might be used by flood forecasters to test operational hydrological models.

Results – Criteria for event selection were established based in part upon the "maximum" falls possible for durations less than 1 hour, and the one in one hundred year return period for greater durations. This resulted in the selection of 50 events comprising 30 convective, 15 predominantly frontal and 5 orographic types. The analysis of these events indicated that extreme events are very unlikely to occur in February, March or April. There is generally a clear distinction between wholly convective and wholly frontal events, and the range of events and types was classified on a depth-duration diagram. It proved possible to develop an achetypal situation that occurred in frontal cases leading to severe convective outbreaks. It appears that Probable Maximum Precipitation (PMP) depths lie between the Flood Estimation Handbook (FEH) extrapolated and Flood Study Report (FSR) values for durations less than about 10 hours.

A decision support methodology for assessing the susceptibility of river catchments to extreme flooding was developed aimed at complementing methodologies already existing in the Environment Agency. The methodology involves a question and answer approach for developing a susceptibility score. It was tested on a selection of extreme events, and evaluated for catchments in North West England. Finally training rainfall data sets for some of the extreme events were presented to enable flood forecasters to test and evaluate operational models and procedures.

Conclusions and Recommendation – The following conclusions and recommendations are presented in the Report: (1) New events should be routinely analysed and tested to see how they fit into the archetypal situation proposed;(2) The Met Office Mesoscale Model can be used to provide details of the synoptic evolution, expected rainfall intensity, accumulation and distribution of rainfall as related to the archetypal situation;(3) A joint Defra/Met Office/EA Project was proposed to establish a prototype 24-hour early warning system;(4) Recent work at the University of Salford on the use of Doppler radar and NWP data to identify extreme convective events should be considered in the context of recommendation (3);(5) A decision support methodology based upon a question and answer scoring scheme seems to offer useful guidance on assessing the susceptibility of river catchments to flooding arising from extreme rainfall, but further assessment and testing are necessary;(6) The rainfall training data sets offer a means of testing operational procedures and models under extreme conditions.

CONTENTS

1 INTRODUCTION

The most extreme hydrometeorological events that are likely to be experienced in the United Kingdom have received only limited study from the point of view of underlying consistency and predictability. Practically all such rainfall and flood events that have occurred in the last 100 years or so have been described, and in some cases have been analysed in order to seek their causes. However, guidance to flood forecasters to help identify these events remains skeletal. It is vital that signals of the possibility of such events be recognised as early as possible, preferably 24 hours or more in advance.

In this report we describe the results of a joint study carried out by the University of Salford and the Met Office on behalf of the Department of the Environment, Food and Rural Affairs (Defra). The aim of the research was to investigate the nature of very extreme rainfall events and the meteorological situations leading to their occurrence, and also the susceptibility of river catchments to their spatial and temporal rainfall patterns. Given that such events are likely to have return periods of many thousands of years, the implications of the analysis for estimates of Probable Maximum Precipitation have also been considered.

2 DEFINITION AND RANGE OF STUDY

The research has addressed those weather incidents occurring over the previous 100 years or so having durations up to about 60 hours. An hydrometeorological event is defined as a specific incident capable of triggering major disruption to human activity. The magnitude of such an incident lies at the extreme of statistical expectation, and may, or may not, lead to loss of life.

Whilst this study has been limited in terms of the resources devoted to it, a wide range of data have been used. The principal data sources are the Met Office archives, the Flood Studies Report (FSR) (1975) and the Flood Estimation Handbook (FEH) (1999).

A subsidiary requirement of this work was to derive training data sets for some extreme events, which might be used by flood forecasters to test operational hydrological models.

3 SELECTION, CLASSIFICATION AND ANALYSIS OF EVENTS

3.1 Selection and classification

Rainfall events that give rise to serious flooding are often outcomes of four main contributory factors. They are intensity and duration of precipitation, the wetness of the ground and the response of the rainfall catchment. The key items considered in this study were the first two, which are the meteorological ones. Hydrological contributions and other factors were noted as and when appropriate.

Criteria for event selection were established by making use of the rainfalls estimated in the Flood Studies Report Volume II (FSR) as the "maximum" falls possible for durations less than 1 hour, and the one in one hundred year return period for durations greater than one hour. Values are shown in table 1 below.

Average Annual Rainfall (AAR) mm	Duration (hours)						
	0.25	0.5	1	24	48	72	96
	Maximum fall (mm) possible			Amount (mm) for 1:100 year return period			
500 – 1400	47	65	83	100	123	135	150
1400 – 2800	**45**	**62**	**79**	**152**	**193**	**219**	**247**
> 2800	43	59	75	228	309	356	410

Table 1. *Maximum falls (mm) possible for durations less than one hour and the one in one hundred year return period for durations greater than one hour as a function of average annual rainfall (AAR). Note that the amounts for greater than one hour correspond to the top of the AAR range.*

Since most "extreme" rainfalls occur over lowland Britain, it was decided to use the middle range of AAR in Table 1 as a definition of the lower limit of extreme rainfalls.

It is useful to compare this classification with the "classification of heavy falls in short periods" by E.G. Bilham published in British Rainfall 1935. Bilham puts falls into three categories - "noteworthy", "remarkable" and "very rare" as shown in Table 2.

Time (mins)	Noteworthy	Remarkable	Very rare
5 or less	10.9	17.3	26.8
10 or less	13.8	21.6	33.2
20 or less	17.3	26.8	40.9
30 or less	19.7	30.3	46.2
60 or less	24.5	37.6	56.8
90 or less	27.8	42.4	64.0
120 or less	30.4	46.2	69.4

Table 2. *Lower limits of rainfall amount as a function of duration for three categories of event according to Bilham 1935. (Note that the original article has a duration resolution of ten minutes).*

Comparing Tables 1 and 2 it can be seen that the lower limit chosen for extreme events is substantially greater than that for the "very rare" category in the Bilham classification.

Event selection was done by searching through a database of "notable rainfall events in the 20th century" held in the Met Office and picking out those that exceeded a curve of values derived from the criteria shown in bold type in Table 1 (see Figure 4). Other sources of information such as the FSR and the British Rainfall series of publications were also utilised to generate the list of extreme events in Table 3.

Date	Location	Total	Duration	Basic type	Reference
12/07/00	Ilkley	95	1.25	Convective	Met.Mag. August 1900 British Rainfall
12/07/01	Maidenhead	92	1	Convective	British Rainfall
21/10/08	Portland (Dorset)	175	5	Frontal***	British Rainfall
09/06/10	Reading	130	2	Convective	British Rainfall
26/08/12	Norwich	186	22	Frontal	British Rainfall
25-26/09/15	Inverness	201	40	Frontal	British Rainfall
16/06/17	Kensington	118	2.3	Convective	Met.Mag. July 1917
28/06/17	Bruton (Somerset)	243	8	Frontal***	British Rainfall
29/05/20	Louth (Lincolnshire)	119	3	Convective	British Rainfall
19/08/24	Brymore (Somerset)	225	5	Convective ***	British Rainfall
19-22/07/30	N. Yorks	250	60	Frontal	British Rainfall
08/08/31	Boston (Lincs)	155	11	Frontal***	British Rainfall
02-03/11/31	W. Britain	240	48	Orographic	Met.Mag. Jan 1932 British Rainfall
11/07/32	Cranwell (Lincs)	126	2	Convective	British Rainfall
26/09/33	Fleet (Hampshire)	131	4	Convective	British Rainfall
22/07/34	West Wickham (Kent)	116	1.66	Convective	British Rainfall
25/06/35	Swainswick (Bath)	150	2.75	Convective ***	British Rainfall
15/07/37	Boston (Lincs)	139	12	Frontal***	British Rainfall
04/08/38	Torquay	127	2.25	Convective ***	Met.Mag. Sept 1938 British Rainfall
16/07/47	Wisley (Surrey)	102	1.25	Convective	British Rainfall
12/08/48	SE Scotland, Tweed	160	12	Frontal	Met.Mag. Jan 1949
15/08/52	Lynmouth	228	12	Frontal***	Met.Mag. Dec 1952 British Rainfall
26/06/53	Eskdalemuir	80	0.5	Convective	Met. Mag. Nov 1953
17-18/12/54	Loch Quoich	254	22.5	Orographic	British Rainfall. DWR.
18/07/55	Martinstown (Dorset)	280	15	Frontal***	British Rainfall
11/06/56	Bradford	165	2	Convective ***	British Rainfall
08/06/57	Camelford (Cornwall)	138	2.5	Convective	Met.Mag. Vol. 86 1957 pp 339-343
05/08/57	Rodsley (Derbyshire)	152	8.5	Convective	British Rainfall
05/09/58	Knockholt (Kent)	131	2.5	Convective	Met.Mag. Oct 1960 British Rainfall

11/07/59	Hindolveston (Norfolk)	93	0.3	Convective	
07/10/60	Horncastle (Lincs)	178	3	Convective ***	
06/06/63	Southery (Norfolk)	150	3	Convective	
18/07/64	Bolton	56	0.25	Convective	
17/12/66	Glen Etive	199	18	Orographic	
08/08/67	Dunsop Valley (Lancs)	117	1.5	Convective	
10/07/68	Chew Stoke (Bristol)	175	9	Frontal***	
15/09/68	Whitstable (Kent)	190	20	Frontal***	Met. Mag. 1974 V103.255-268, 288-300.
31/10/68	Tollymore Park (Co.Down)	159	24	Frontal	
11/06/70	Pershore	67	0.4	Convective	
27/06/70	Wisbech	51	0.2	Convective	
01/08/73	Norwich	138	4	Convective	
20/09/73	West Stourmouth (Kent)	191	24	Frontal	
09/11/73	Blaneau Ffestiniog	147	15	Orographic	
17/01/74	Loch Sloy	238	30	Orographic	
14/08/75	Hampstead	171	3	Convective	Met. Mag. June 1981
25/06/80	Sevenoaks	116	1.75	Convective	Met. Mag. V109 1980 pp 362-363
01/08/80	Orra Beg (Antrim)	97	0.75	Convective	
05/08/81	Tarporley (Cheshire)	132	5	Convective	
19/05/89	Walshaw Dean (Halifax)	193	2	Convective	Weather. Vol 46 7;1991
31/08/94	Bungay (East Anglia)	146	12	Frontal	

Table 3. *List of extreme event dates showing date, location, rainfall amount (mm) and duration (h), classification and published source of additional information. In the classifications, frontal*** indicates a significant convective component and convective*** indicates significant frontal forcing.*

3.2 Data sources used for analysis of events

Up to 1960 the British Rainfall series of annual publications was invaluable for providing detailed rainfall information for each event and also on most occasions a brief description (sometimes with maps) of the meteorological conditions and associated flooding. Some events were also published in the Meteorological Magazine (Met. Mag.) and referenced by British Rainfall. Descriptions of events were often from interested members of the public who gave valuable insights into the possible nature of the system responsible for the event. Two examples are as follows; " *Sir, - On Thursday afternoon, July 12th, a terrific thunderstorm raged over a part of the West Riding of Yorkshire, beginning in the west about noon, and extending or propagating itself gradually eastwards. The direction of the thunder* *clouds was from S to N, although as is usual in such cases, the surface winds were very variable under the storm area, and in the district to the eastward the sky was very clear and blue, and a strong easterly wind blew into towards the storm centre ... "* That was part of a description of the Ilkley storm in 1900 published in Met. Mag.. More recently we have the following extract - *"At Hedgebarton, 15 miles to the northwest of Torquay, Mr W.K. Kitson noted that the rain did not begin until 4h 15m and by 8h as much as 5.86 inches was recorded. Very large hailstones occurred but the hail was of short duration. For four hours the lightning appeared to be continuous. It appeared to be a purely local storm confined to an area a mile in diameter and other localities appear to have had purely local storms. "* which was part of an account of the storm of 4/8/38 in British Rainfall.

After 1960 the British Rainfall series changed style and was much less useful for this study and additional information had to be gleaned from the Met Office Daily Weather Report (DWR) series and published articles. It is perhaps ironic that the early events were better recorded in detail but the underlying meteorological information was less good than in more recent years.

Upper air data were only available from the 1920s, radar data from the 1950s and satellite data from the 1960s. Moreover it was only in the 1930s that fronts were routinely analysed on charts published in the DWR so for the early events these had to be professionally inferred from available data.

Flooding information was also well documented and easy to determine in British Rainfall prior to 1960 but less so after that date.

3.3 Basic analysis of events

Out of the 50 cases, (coincidentally a round number), there were 30 assessed to be predominantly convective, 15 predominantly frontal and 5 orographic types. Although in many cases orography was a contributing factor due to forced ascent of moist air, the cases deemed to be orographic were where general orographic uplift was the dominant mechanism for the very high rainfall. The distributions of events throughout the 20th Century are shown in Figures 1 and 2.

Figure 1. Number of extreme events per decade

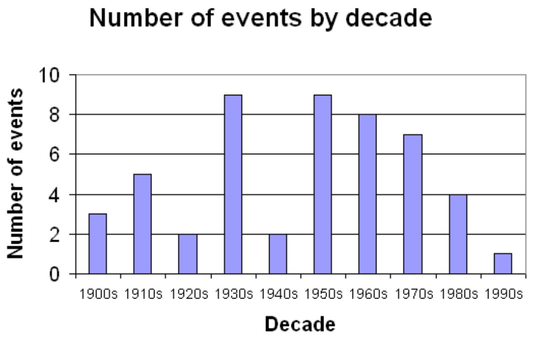
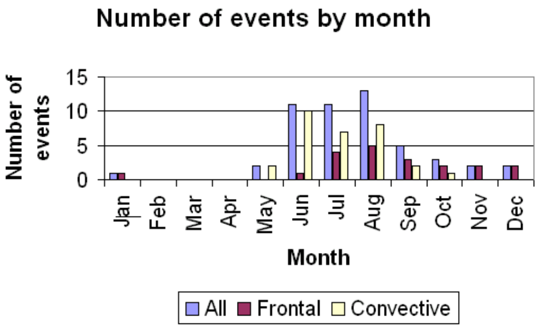


Figure 2. Number of extreme



events per month and type
(frontal type includes orographic)

The distribution per decade (Figure 1) indicates no significant variation during the century with the 1930s and 1950s having most cases and more cases in the second half of the 20th century than in the first. However, no conclusions should be drawn from this since the first half included two world wars and a less extensive network of professionally maintained rainfall gauges. A steady decline in the annual number of events from the 1950s to the 1990s is also noted. Whilst this is not yet statistically significant one is tempted to associate it with a changing climate.

The monthly distribution (Figure 2) is more interesting. There were no events in February, March or April. Most events occurred during the summer months with a rapid increase in number in June with a gradual tailing off during the autumn. Naturally convective events tail off more quickly than frontal ones with no convective events in November, December or January since insolation is an important forcing factor for convection. An explanation for this highly skewed distribution of extreme events is that relatively low sea temperatures and colder air during the Spring would mean less available moisture for rain producing systems. Even though atmospheric instability can be high in April, these results would suggest that although shower events can be sharp at that time of year, they are not capable *by themselves* of providing extreme rainfalls. It is also interesting to compare the minimum temperature distribution of a typical inland location like Manchester Airport (Figure 3) with the monthly extreme event distribution. The 1961-1990 monthly minimum temperature distribution is similarly skewed with higher values in the autumn compared to the spring months as a consequence of higher soil and sea temperatures.

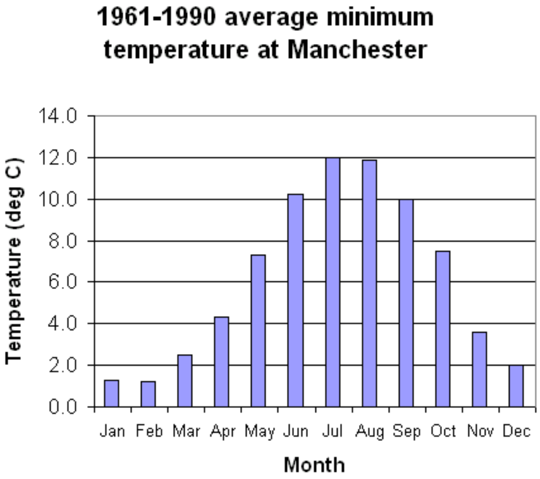


Figure 3. *Monthly distribution of minimum temperature at Manchester*

Going through the cases it soon became obvious that a number of the frontal cases had a significant convective element. This was usually characterised by embedded thunderstorms shown plotted within a general band of otherwise frontal dynamical precipitation, for example, Lynmouth 1952.

Similarly some convective events arose due to instability being released due to the presence of an otherwise inactive front, for example, Bradford, 1956. These cases are labelled with *** in Table 3.

The basic classifications in Table 3 are shown in graphical form as a function of rainfall amount and duration in Figure 4. In the area of the graph above the plotted points lie values of Probable Maximum Precipitation (PMP) for each duration. We discuss this later in section 5.

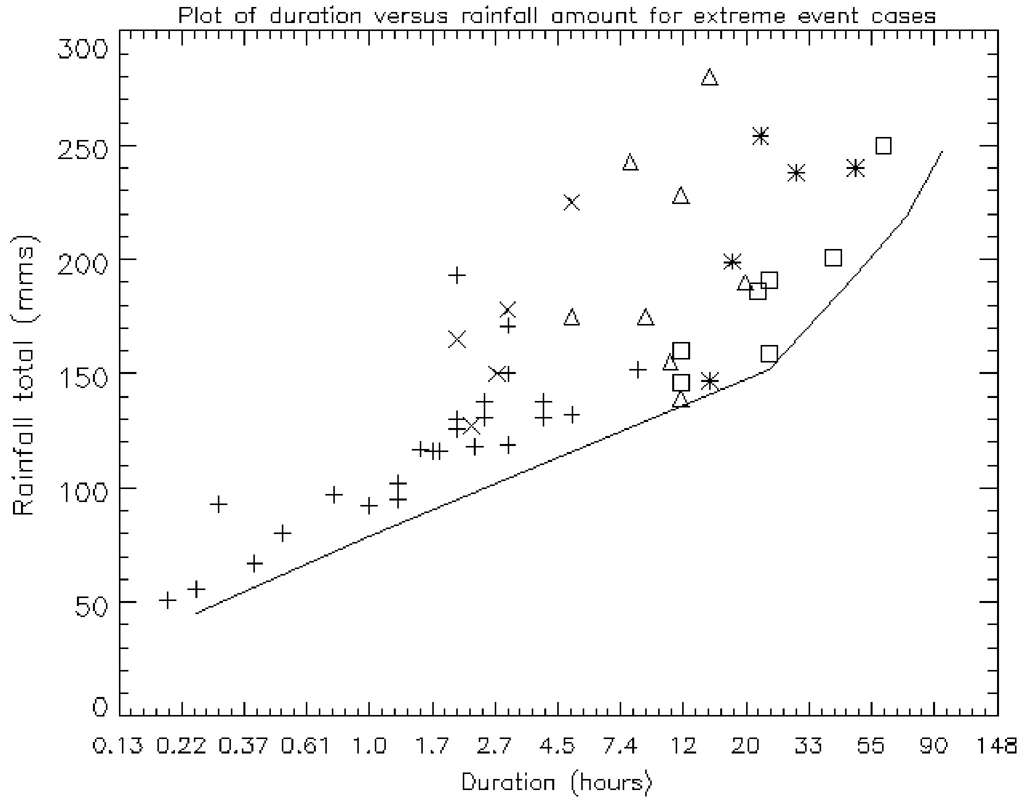


Figure 4. *Plot of rainfall amount (mm) versus duration (h) (on a logarithmic scale) for each of the five event categories listed in table 3. '+' = convective , 'X' = convective*** (frontal forcing), * = orographic, Δ = frontal*** (with embedded instability) and 'square' = frontal. The solid line plot indicates the lowest threshold used for extreme event classification as in table 1.*

This graph is interesting in that the convective cases seem to be closely scattered about a well-defined line. The scatter increases for durations greater than about 2 hours when convective cases with dynamical forcing become included. The frontal events are also grouped so as to increase linearly but with more scatter than the convective cases with some notable outliers. The largest rainfall amounts for specific durations occurred in cases where there was significant embedded instability, for example, Bruton 1917, Lynmouth 1952 and Martinstown 1955. Events below the line in Figure 4 have not been considered although it may be that such events fall into the classifications shown in the same way.

As well as meteorological features some hydrological aspects were examined using the comprehensive and detailed information in the British Rainfall series up to 1960 and in the 1968 edition. Out of the 34 cases up to and including 7/10/60 and the 1968 cases, 94% of the rainfalls caused flooding. A lot of the flooding was serious and damaging, and in some cases tragic, as at Louth in 1920 and Lynmouth in 1952. In the two non-flooding cases (11/7/32, 26/9/33) there was no mention of widespread flooding though it would be surprising if local flooding did not occur given the intensity of the rainfall on those occasions. Deluges of water cascading quickly down hillsides, for example at Ilkley in 1900 caused several serious events. A major factor in the Lynmouth and Louth floods was build up of water behind debris, which subsequently burst to give catastrophic results. Looking at the rainfall events in the two months prior to each extreme case, an estimate was made of the wetness of the ground. 34% of the cases in the sample were estimated to have very wet ground beforehand, undoubtedly contributing to flooding. (In the two non-flooding cases the ground was not wet prior to the event). This analysis implies that all extreme rainfall events are highly likely to give some sort of flooding problems, which will be exacerbated if the rainfall falls in sensitive catchments, over steep orography or over already very wet ground.

3.4 Analysis of events

3.4.1 Orographic events

There were 5 cases in the sample; 2-3/11/31, 17-18/12/54, 17/12/66, 9/11/73 and 17/1/74. Note that all of these events were in the months November, December and January. All cases involved a long sea fetch (greater than 2000 Km) in a strong west to southwest straight airflow with a high pressure region centred either over the Bay of Biscay (12/54, 12/66, 11/73, 01/74) or Greece with a ridge to Spain (11/31) as summarised in Table 4.

Event	Amount (mm)	Duration (h)	Fetch direction	Fetch distance (km)	600m wind speed (m/s)	Source dewpoint (deg C)
2-3/11/31	240	48	SW	2500	25	17
17-18/12/54	254	23	WSW	3000	25	14
17/12/66	199	18	WSW	3500	25	18
9/11/73	147	15	WSW	2000	15	16
17/01/74	238	30	WSW	4000	25	15

Table 4. *List of orographic events giving rainfall amount and duration, the fetch of the airmass specifying direction and distance, estimated mean wind speed along fetch at 600m (from surface isobars) and the estimated airmass source dewpoint.*

The key parameters from the sample would seem to be fetch (direction and distance), wind speed and a moist and warm tropical maritime airmass. The large values of fetch are not uncommon with winds from the WSW or SW directions over the Atlantic.

An example of a typical synoptic situation that could lead to extreme orographic rainfall is shown in Figure 5 for 17/12/66. The high rainfall occurred over western Scotland in the strong to gale force warm sector west-southwesterlies behind the warm front. Note the long fetch of warm and moist air which has air temperatures in the source region around 21 deg C.

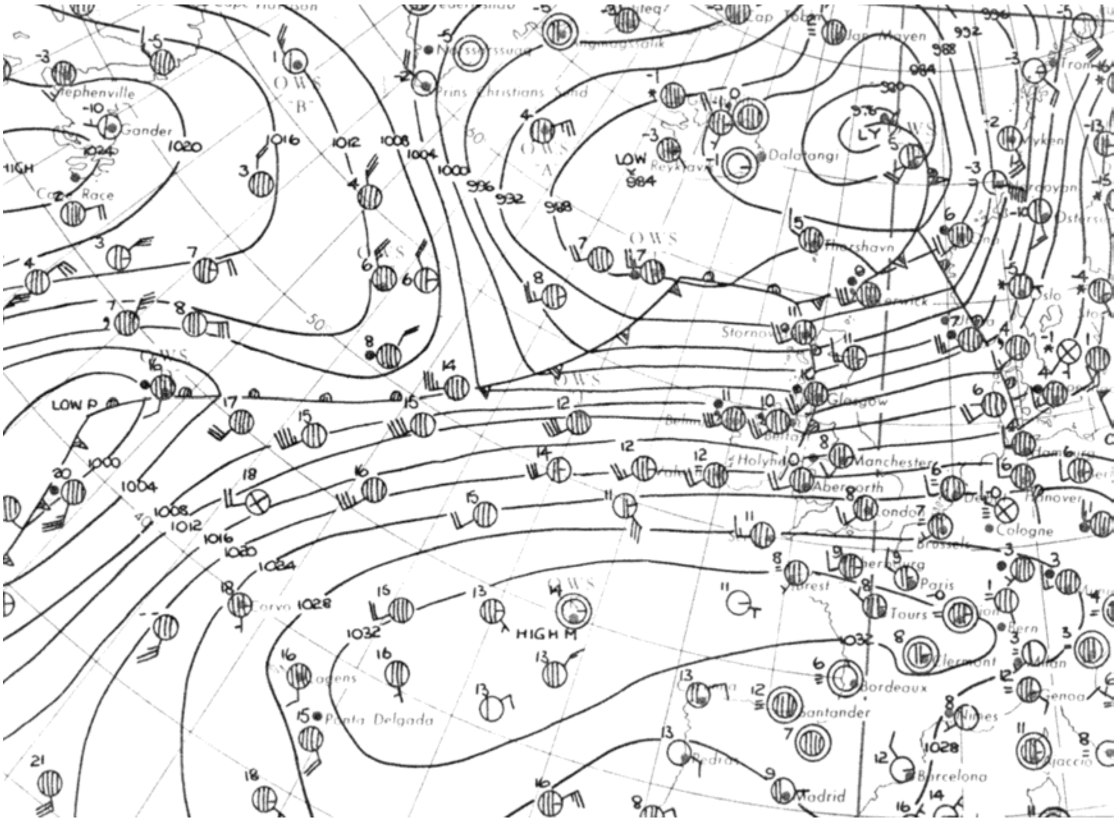


Figure 5. *Surface chart for 1200 GMT 17/12/66 (from DWR).*

3.4.2 Frontal events

Looking at the surface synoptic charts for all of the 15 frontal cases (excluding orographic ones) it quickly became obvious that all of the events were either associated with a slow moving frontal system or a depression that was close by, and in 10 cases a combination of both.

Figure 6 shows the aspect of each frontal event in relation to the depression centre. For example a square on the arm labelled 'W' at '-200' would mean that the event occurred 200 Km to the west of the depression.

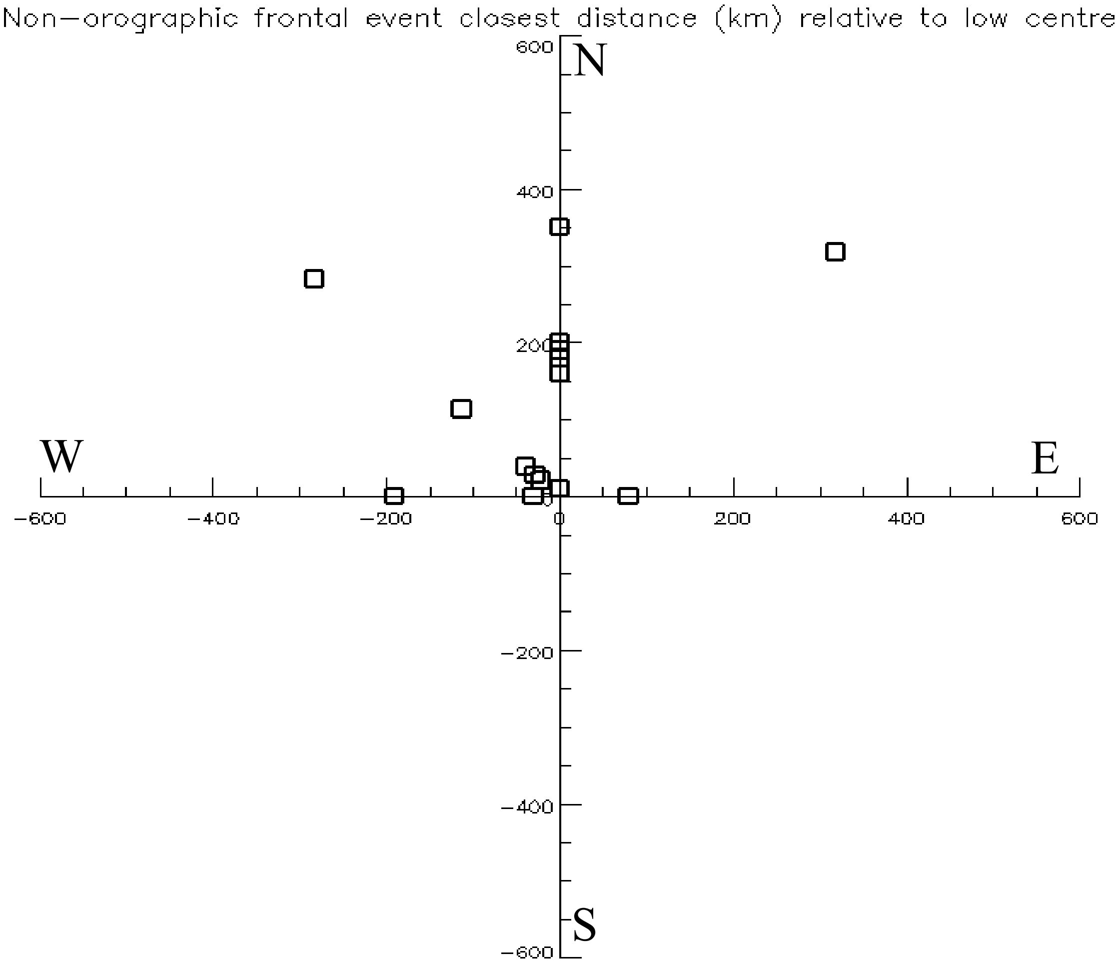


Figure 6. *Direction and closest distance of each frontal event from closest approach of depression centre (0 on the compass cross). (See text for more details).*

None of the 15 frontal events were greater than 450 Km at their closest point from a depression and 75% (12/15) were within 200 Km. In terms of aspect, all events occurred north of a depression and 73% either northwest (NW) or north (N). 60% (9/15) were both NW or N and within 200 Km at closest distance from the low pressure centre. Of those 60%, 6 out of 8 had significant embedded instability (frontal*** category) and 3 out of 7 had little evidence of instability. In 12 out of the 15 cases the speed of the low was less than or equal to 10 m/s and in 7 out of the 15 cases it was less than or equal to 5 m/s.

In 75% (12/15) of cases a slow moving frontal system was involved in the situation. It is interesting to note that the frontal event (Martinstown, 1955) that gave the most rainfall (280 mm in 15 hours) was an almost stationary front extending almost due west to east across southern England with embedded instability.

Since most of the fronts were either to the east or south of the event the rain producing system naturally involved the northward or westward advection and ascent of very moist and relatively warm air. A very good example of this is illustrated in the January 1949 Met. Mag. Article of the 12/8/48 "Tweed floods" and also in Figure 7.

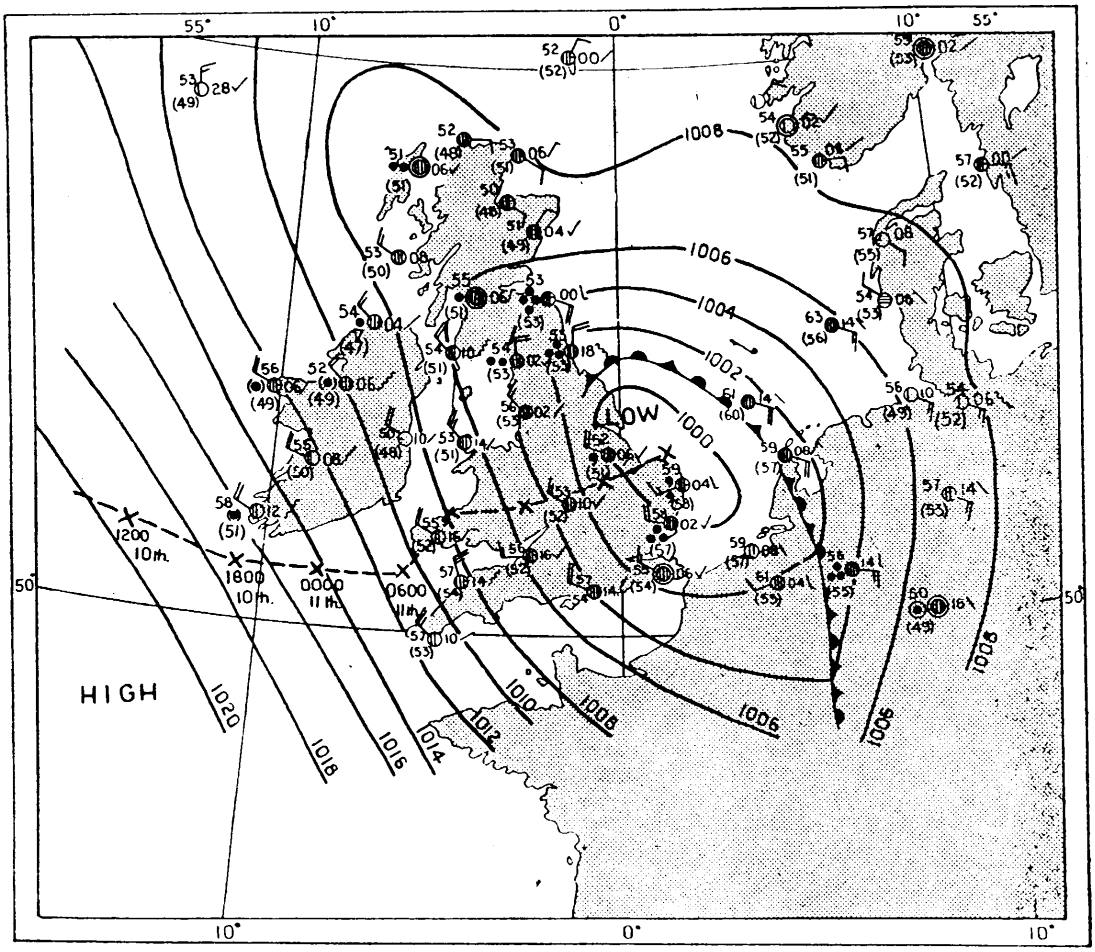


Figure 7. *Surface chart showing movement of depression and associated frontal system and position of low centre at 0600 UTC 12/8/48. (Reproduced from Glasspoole in Met. Mag. 1949).*

The low pressure centre is clearly seen tracking to the south of the Tweed across England with a slow moving warm occlusion to the north providing the prolonged and heavy rainfall.

A fairly similar example on 21/7/30 is shown in Figure 8.

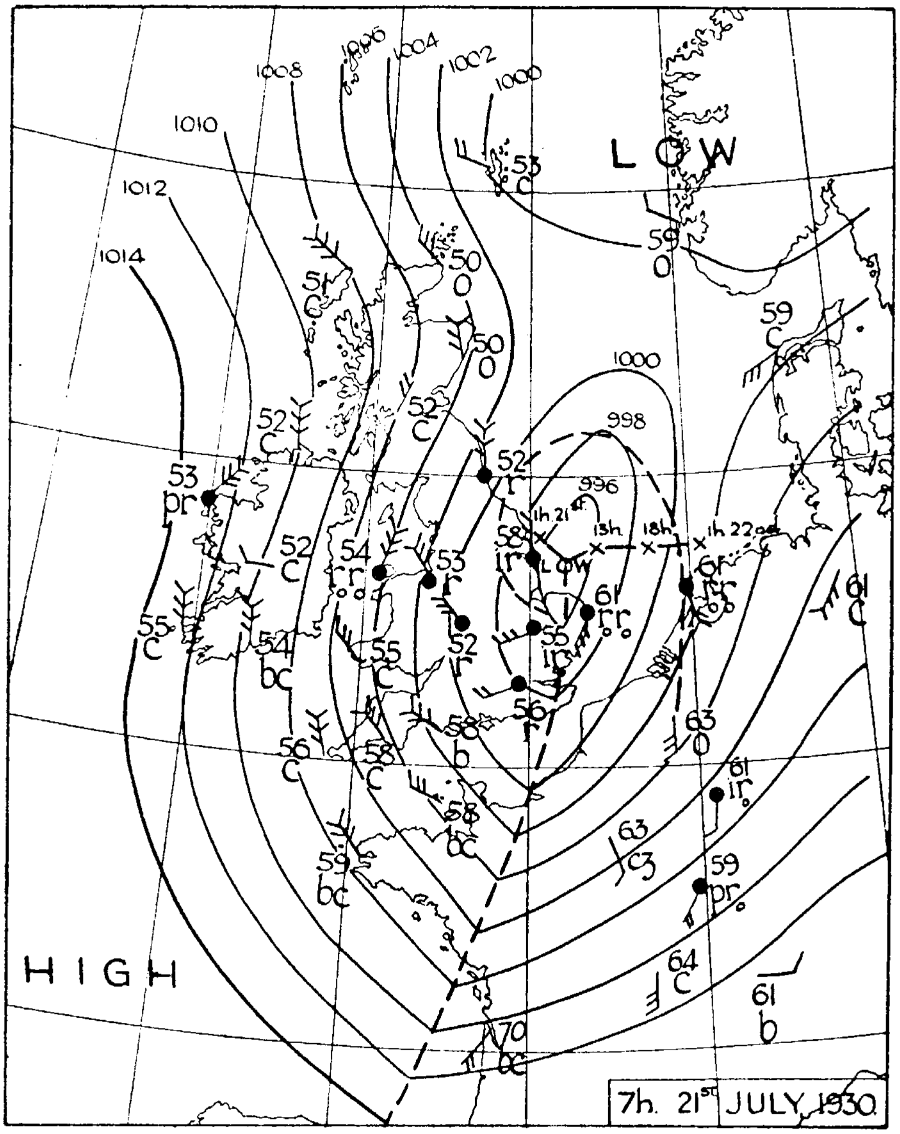


Figure 8. *Surface chart for 0700 UTC 21/7/30. The movement and position of the low at other times is indicated by crosses and the position of fronts by dashed lines. The number of wind feathers indicate Beaufort force. (Reproduced from British Rainfall).*

The rainfall event in north Yorkshire was to the west of the low which moved very slowly east during 21st to 22nd July. The dashed line indicating a front curving round the north and west of the low was probably a slow moving warm occlusion similar to the 1948 case.

The chart for the Lynmouth flood event is shown in Figure 9.

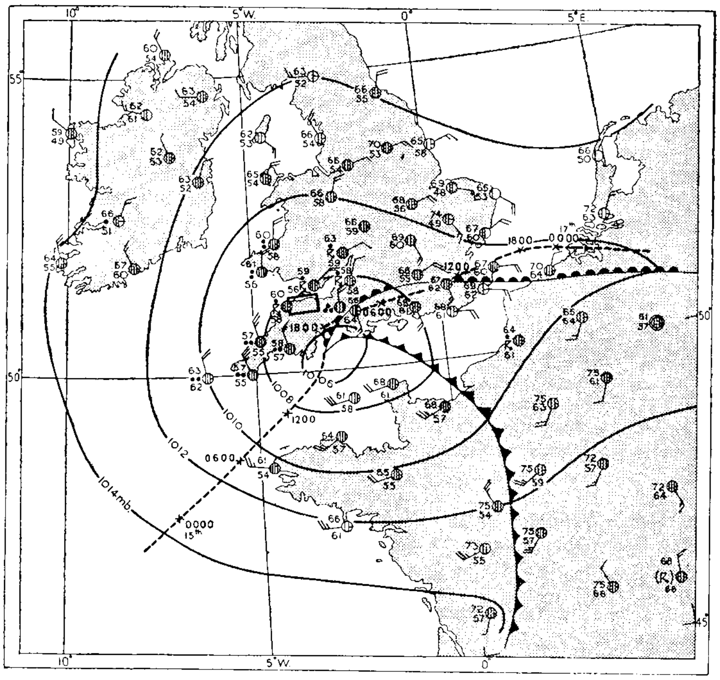


Figure 9. *Synoptic chart for 1500 UTC 15/8/52. (Reproduced from Bleasdale and Douglas in Met. Mag. 1952).*

This again shows a slow moving depression running close and to the southeast of the extreme event. A key feature is the advection of very moist air (indicated by the warm front) northwestwards into the potentially unstable region over Exmoor lying just to the east of an upper trough.

The final example is for 15/9/68 and is shown in figure 10. Again note the very heavy rainfall to the north and west of a small low pressure centre in association with a well-marked warm occlusion with much embedded instability.

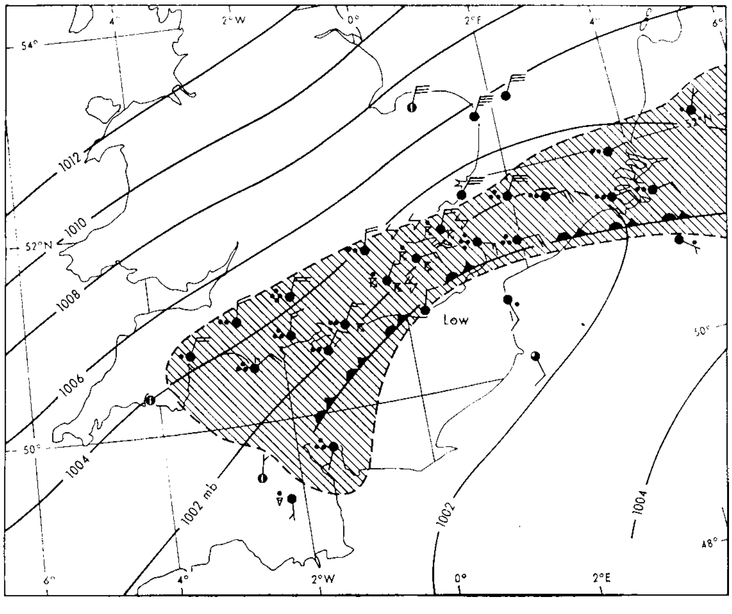


Figure 10. *Synoptic chart for 0900 UTC 15/9/68. (Reproduced from Salter and Richards Met. Mag. 1974).*

3.4.3 Convective events

The convective events broadly fell into two categories:

(a) Either where forcing was from a synoptic scale feature such as a front, or updraughts and downdraughts in the system were very strong with a high value of convectively available potential energy (CAPE).

(b) Forcing was either from insolation or a meso-scale feature such as a convergence line or sea breeze and smaller values of CAPE.

Identification of cases where frontal forcing was dominant was straightforward by looking at sequences of plotted observations and reading published accounts. Assessment of CAPE was somewhat laborious with limited upper air information. Therefore, in most cases accounts and observations of large hail were used as a proxy. Hail was reported in a lot of the cases as would be expected in extreme convective events but special mention tended to be made in publications when the hail was large enough to damage crops, greenhouses and other property. These cases were put into category (a). However, in a few cases available data and information were insufficient in order to determine the cause of the convective event. These cases were put into category (b).

The categorization of convective events is shown in Table 5.

	Evidence/cause	Reference
Type (a) events		
09/06/10	Large clusters of rainfall. Large hail.	British Rainfall
16/06/17	Strong vertical wind shear. Large hail.	Met.Mag. July 1917
19/08/24	Trough/cold front ? Substantial hailfall.	British Rainfall
11/07/32	Sea breeze convergence ? Large hail.	British Rainfall
25/06/35	Occlusion. Wind shear. Large hail.	British Rainfall
04/08/38	Occlusion. Wind shear. Large hail.	Met.Mag. Sept.1938
11/06/56	Slow moving frontal zone.	British Rainfall. DWR.
08/06/57	"Unusually heavy hail"	Met.Mag.1957 pp339-343
05/09/58	Large CAPE. "Tennis ball" hail. Tornado.	Met.Mag. Oct. 1960
11/07/59	Trough/small low. Large hail.	DWR.
07/10/60	General thundery rain.	DWR.
06/06/63	Thundery rain. Large hail.	DWR.
14/08/75	Local insolation. Multicell. Large CAPE.	Met.Mag. June 1981
25/06/80	Trough ? Prolonged hailfall.	Met.Mag.1980 pp362-363
19/05/89	Old front in region. Multicell.	Weather Vol 46 7;1991
Type (b) events		
12/07/00	Convergence ? Possible multicell ?	Met. Mag. Aug.1900
12/07/01	Convergence ?	British Rainfall
29/05/20	Trough. Convergence. Line.	British Rainfall
26/09/33	General instability release in easterly.	British Rainfall
22/07/34	Trough ? Squall-like.	British Rainfall
16/07/47	Upper part of split cold front ?	British Rainfall
26/06/53	Convergence. Unstable northerly flow.	British Rainfall. DWR.
05/08/57	Clusters.	British Rainfall
18/07/64	Line. Low pressure over Wales.	DWR.
08/08/67	Orography ?	DWR.
11/06/70	Cluster. Insolation ?	DWR.
27/06/70	Line. Front.	DWR.
01/08/73	Sea breeze ?	DWR.
01/08/80		DWR.
05/08/81	Old fronts.	DWR.

Table 5. Categorization of convective events into type (a) and (b). (See text for details). An indication of the likely cause of the event and other evidence is shown as well as the reference source of the evidence.

Events that contained large hail and events that did not are plotted in Figure 11.

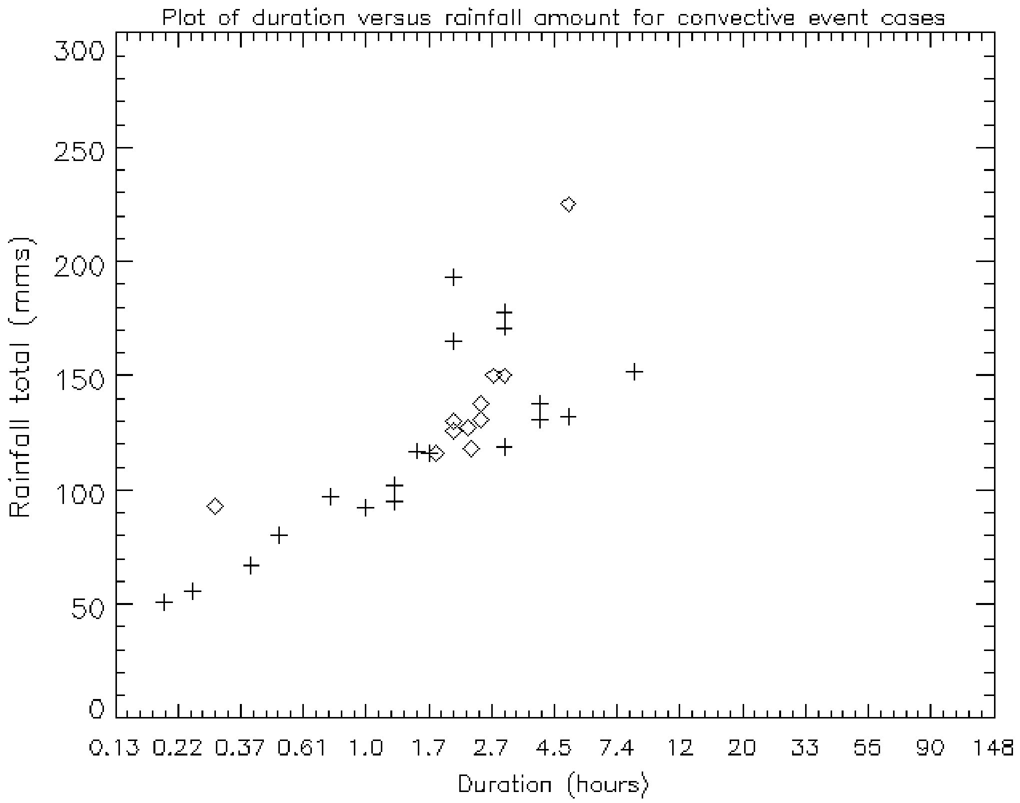


Figure 11. *Plot of rainfall amount (mm) versus duration (h) for the convective event cases. Crosses indicate events where there was no evidence of large hail and diamonds indicate cases where large hail was reported.*

This analysis shows a tight group of cases with large hail with durations in the range 2-3 hours. The non-hail cases in that range are all type (a) cases - 11/6/56, 7/10/60, 14/8/75 (multicell) and 19/5/89 (multicell). There are two outlier large hail events - 11/7/59 and 19/8/24.

This diagram is very encouraging as it implies that if we can identify storms that are likely to have large and damaging hail then we will have some idea of the possible nature of the storm in terms of rainfall duration and amount. Moreover, if storms that have strong frontal forcing or large CAPE are included then there is a good separation on the diagram (see section 7).

Unlike the frontal and orographic cases it was not possible to identify common synoptic causes. Each case was different in some aspect of detail and an extreme event would not necessarily occur given a similar looking synoptic pattern on another occasion. However, looking in broad terms it was found that out of the 30 convective events, 16 were "weakly forced". Weakly forced means that there was no discernible triggering mechanism on the synoptic scale, however, potential instability could be released by meso-scale features such as troughs, convergence lines, sea breezes, temperature hot-spots, local orography etc. It was also encouraging that only 33% of type (a) cases were weakly forced (those that were, produced multi-cells or large hail) whereas 73% of type (b) cases were weakly forced.

A good example of a weakly forced situation is provided by the Hampstead storm of 1975 where the general synoptic situation is shown in Figure 12.

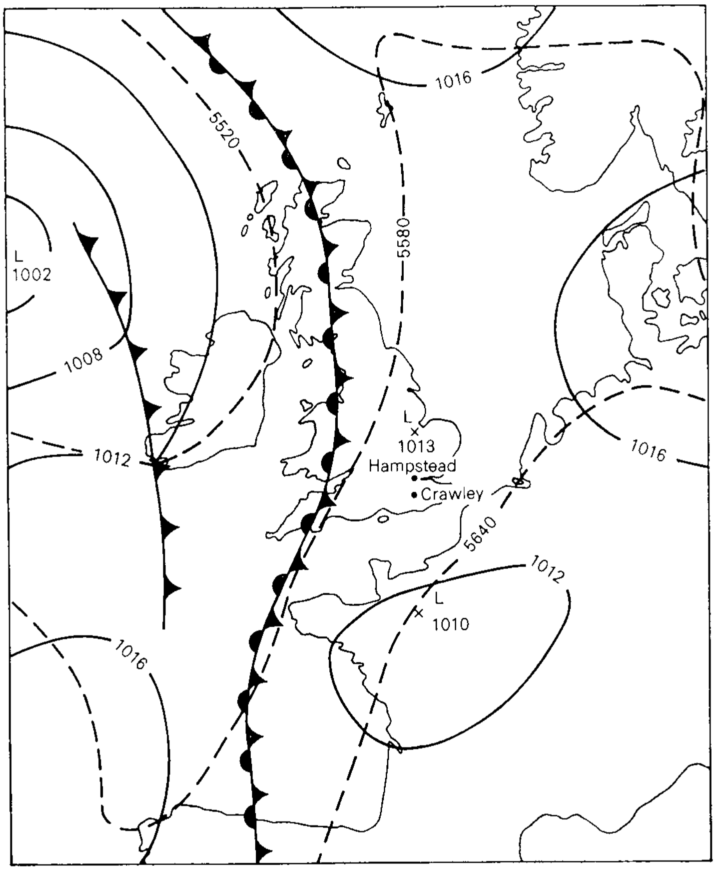


Figure 12. *Synoptic situation over the British Isles at 1200 UTC 14/8/75. (Reproduced from Bailey, Carpenter, Lowther and Passant in Met. Mag. 1981).*

The situation was fairly static with a stationary front over Wales and SW England with very warm air to the east of it. Thunderstorms were thought to be triggered by a combination of the London heat island and the effect of Hampstead hill. Once triggered the storm maintained itself for 3 hours due to the development of new convective cells very close to previously active ones.

A surface chart for a case that was not weakly forced is shown in Figure 13.

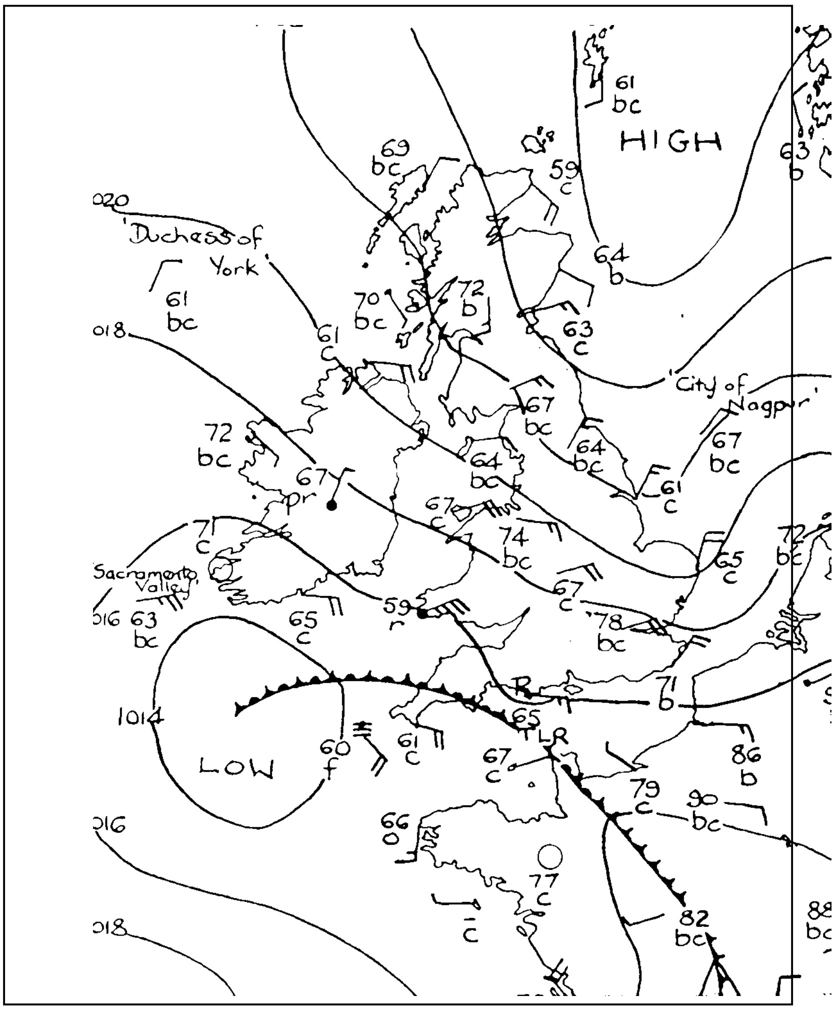


Figure 13. *Surface synoptic chart for 1300 UTC 4/8/38. (Reproduced from Met. Mag. 1938).*

It was very clear that on this occasion the thunderstorms in the Torquay area were triggered by the cold occlusion which had lost most of its frontal precipitation but still remained active as an airmass discontinuity with associated upward air motion.

All of the fronts in the convective cases where the primary triggering mechanism was frontal were of the cold type, i.e. either a cold front, cold occlusion or trough.

3.4.4 Combined analysis of frontal and convective events

Bringing together the findings in sections 5 and 6 a diagram (see Figure 14) was constructed showing four types of extreme rainfall event.

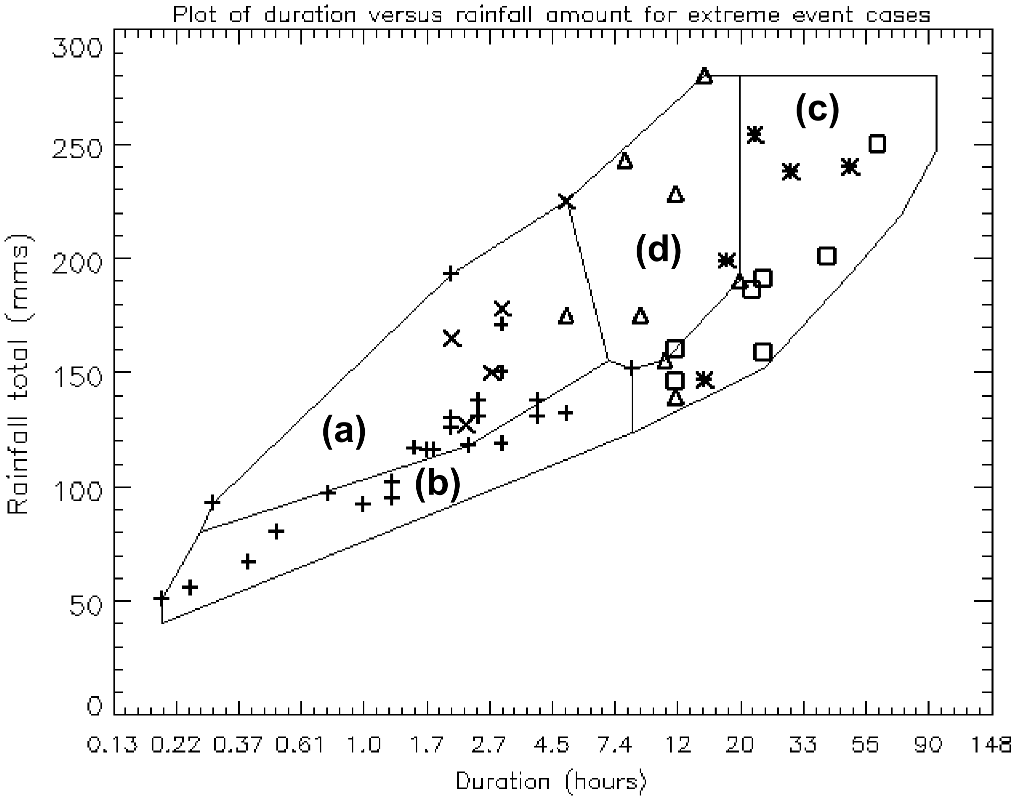


Figure 14. *Diagram showing different regions labelled (a), (b), (c) and (d), which correspond to different types of extreme rainfall event. See text for details. Individual events are marked with '+' = convective , 'X' = convective*** (frontal forcing), * = orographic, Δ = frontal*** (with embedded instability) and 'square' = frontal.*

The types of event in the diagram are as follows:

(a) Severe convective events that are triggered by synoptic scale cold frontal forcing or have large hail. This class also includes isolated near stationary clusters and large multicells in a strongly sheared environment. Duration 0-5 h totals 80 – 220 mm.

(b) Convective events triggered by mesoscale features (e.g. convergence, sea breezes, troughs, upper cold pools, orography or local heating). These events may also have hail but the hail should not be large and damaging or be very prolonged. Some multicellular organisation may also be possible but should not be too self-organizing or long lasting. Duration 0-8 h totals 40 – 150 mm.

(c) Prolonged frontal or orographic events that have little or no convective element. Duration 8 – 90 h totals 120 – 280 mm.

(d) Frontal (widespread rainfall) events that have a significant convective element (embedded instability). Duration 5 – 20 h totals 150 – 280 mm.

3.5 Conclusions

This work has been conducted in such a fashion so that the conclusions and recommendations have been driven by evidence from the case studies without any pre-conceptions. The aim of this work was not to describe a set of case studies but to draw together all the case study evidence into something useful and applicable overall. However, the event references should be useful as a reference for future study and the development of training material for practitioners. The following conclusions are drawn.

- Extreme rainfall events are very unlikely to occur in February, March or April.

- Convective events are most likely in June, July, and August and are very unlikely in November, December, January, February, March or April.

- An extreme rainfall event is highly likely to produce serious flooding situations particularly if it occurs over a sensitive catchment or steep orography or when the ground is already very wet from previous rainfalls.

- There was generally a clear distinction between wholly convective and wholly frontal events but with 25% of cases being a mixture of both.

- All frontal cases involved prolonged ascent of very moist air with 75% of cases having a depression pass slowly by within 200 Km at closest approach to the south or east of the event.

- 75% of frontal cases also involved a slow moving front, usually a warm occlusion, in the situation.

- Frontal cases with embedded instability (53%) generally produced larger totals for a given duration and were close to a depression centre.

- An archetypal situation that occurred in several frontal cases leading to severe convective outbreaks is shown below in Figure 15. Such a situation would cover particularly types (a), (b) and (d) in Figure 14.

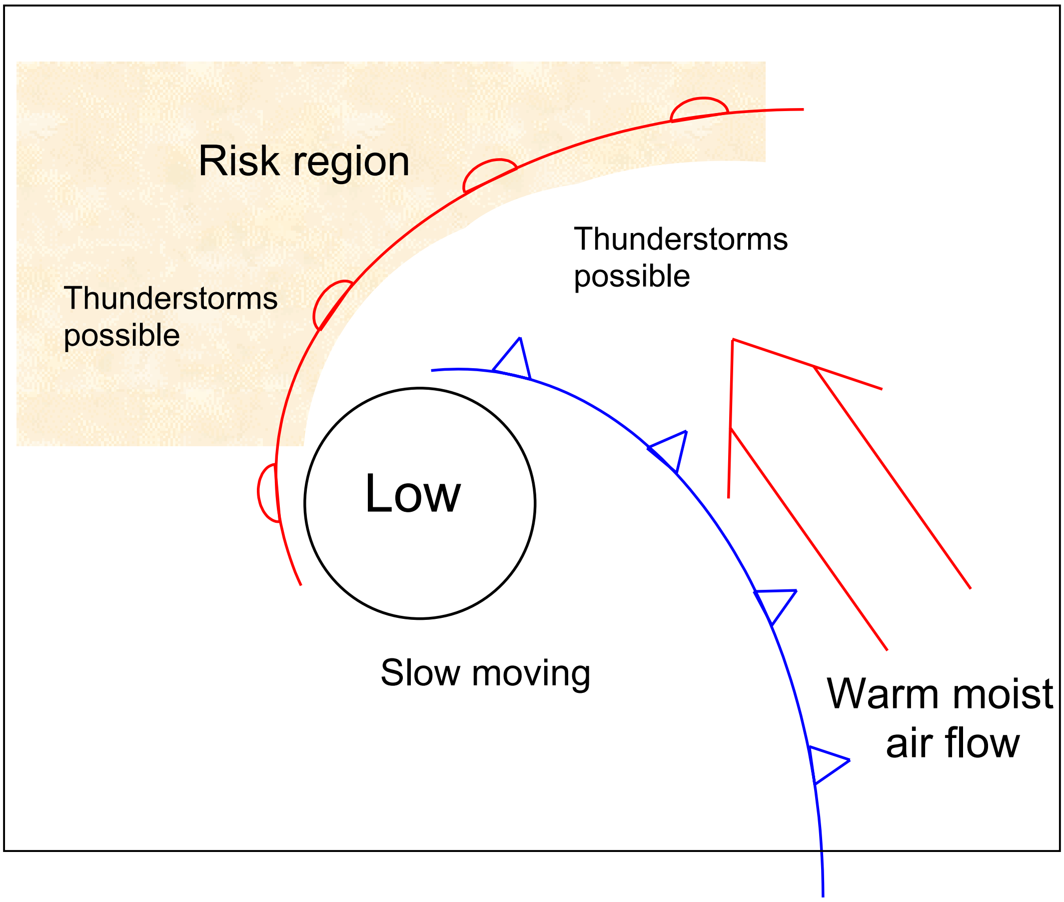


Figure 15. *Schematic diagram showing archetypal situation that occurred in several of the extreme frontal events. The main region at risk of extreme rainfall is shaded. Cold front is shown with blue 'spikes' and warm front with red 'bobbles'. The direction of the main warm and moist airflow is shown by the broad red arrow. (See text for interpretation).*

The schematic illustrates the main features that occurred in 10 out of 15 of the frontal cases; 21/10/08, 26/08/12, 22/07/30, 15/07/37, 12/08/48, 15/08/52, 10/07/68, 15/09/68, 20/09/73 and 31/08/94. Although details and orientations were different the key similarities were a slow moving low within 200 Km of the event, a warm moist ascending airflow marked by a slow moving warm front or occlusion, the possibility of instability release leading to thunderstorms either close to the low centre or within the ascending warm airmass, the extreme rainfall either along the warm front (occlusion) or in the northwest quadrant relative to the low centre.

- All orographic events occurred in either December, January or February and were associated with a high pressure region over the Bay of Biscay or Spain with a very strong west to southwest flow with a fetch greater than 2000 Km persisting for 15 hours or more. The dewpoint of the air in the source region was estimated to be greater than 14 deg C and the average geostrophic (600m) wind along the fetch was greater than 15 m/s.

- Convective events were either weakly forced (potentially unstable) or associated with large synoptic features such as a cold front or occlusion. The presence of large hail was very useful for discriminating the more severe events.

- All events can be categorized into four basic types, (five if orographic events are considered separately), which could form the basis of future work in devising methods for formulating 24 hour early warnings of extreme rainfall.

- Training data sets for a range of extreme events are given in Appendix A.

4. IMPLICATION OF WORK FOR PROBABLE MAXIMUM PRECIPITATION (PMP) ESTIMATION

4.1 Definition and return period

The Probable Maximum Precipitation (PMP) is assumed to be the physical upper limit to the amount of rain which can fall in a given time. Collier and Hardaker (1996) derived the risk of having a severe thunderstorm at a place by considering the separate risks of having a storm take place, the risk that the storm will happen at a particular place, the risk of having large convergence due to the storm and the risk that storm-induced winds will be at right angles to the maximum orographic gradient. This led to the estimation of the return period for convective storms of a few hours duration of about 10^4 years. Consideration of storms known as Mesoscale Convective Systems (Browning and Hill, 1984) suggested that the return period for these systems having durations from 12 to 24 hours is about $2.5.\ 10^5$ years. For longer duration storms the PMP return period may well be larger than this value.

4.2 Flood Studies Report (FSR) and Flood Estimation Handbook (FEH)

The FEH, published in 1999, describes the methodology which is currently the standard for estimating rainfall and flood return periods for any duration. This work supercedes the FSR, published in 1975, for rainfall durations from 1 hour to 8 days, but does not contain any updated methodology for durations outside the range. Of particular concern here is the observation that there is no update to methods of calculated PMP.

Recently engineers have pointed out (MacDonald and Scott, 2002) that extrapolation of FEH techniques to estimate PMP does not seem to be acceptable as it produces much larger estimates of PMP than those derived using the FSR. This is not surprising as the FEH deferred to the FSR for PMP estimation. However, an acknowledged weakness of the FSR was the lack of `regional' rainfall information, and this weakness has been particularly evident in South West England (Clarke, 1995), and, more generally, for durations up to 24 hours (Collier and Hardaker, 1996).

4.3 Implications of current analysis for PMP

Fig. 16 shows the Depth-Duration plot for the identified extreme events. Also shown are the FSR point area and area PMP values, and the FEH PMP values derived for Waddington (Lincolnshire). It is clear that some extreme events for durations from about 2 to 12 hours exceed the FSR PMP values. On the other hand FEH PMP values are much larger than the observed storm totals for short durations, but approach the observations for durations between 10 and 24 hours. Note the Halifax storm which had a return period of 6000 years.

It would appear that appropriate PMP depths lie between the FEH extrapolated and FSR values for durations less than about 10 hours, and between 10 and 24 hours appropriate PMP depths may be derived by extrapolating the FEH statistical analysis or using some modified Clarke (1995) technique. However, such conclusions needs further detailed consideration and support before a "best practice" procedure can be evolved. Both the FEH and Clarke (1995) techniques use different statistical extrapolation methodologies and it is not clear which is appropriate for the storm dynamics in this duration range.

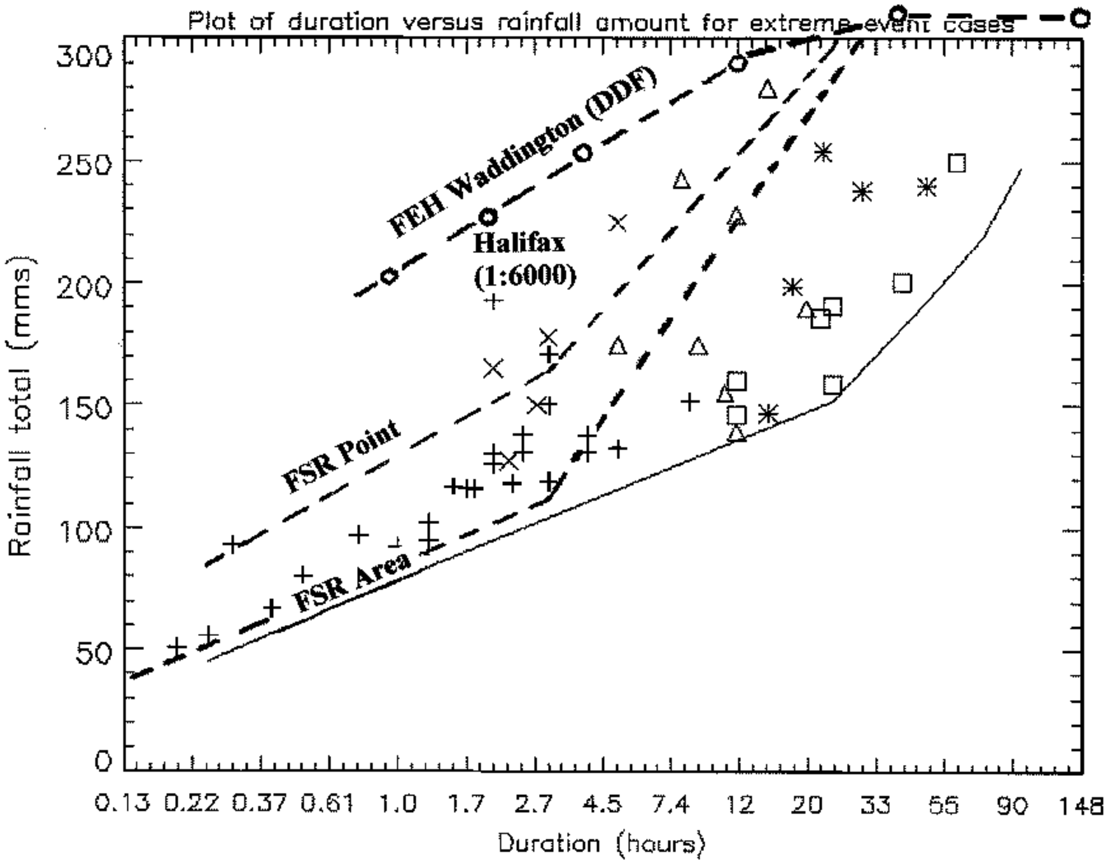


Figure 16: Plot of rainfall (mm) versus duration (h) for different rainfall types. Also shown are the estimates of PMP derived from the FSR and the FEH (dashed lines) for Waddington (Lincolnshire). Symbols are the same as shown on Fig 14. The solid line indicates the lowest threshold used for the extreme event classification as in Table 1.

5. ASSESSING THE FLOODING SUSCEPTIBILITY OF RIVER CATCHMENTS TO EXTREME RAINFALL

5.1 Background

The Environment Agency (EA) in the United Kingdom, in response to the Bye report (1998), has recently introduced a new system of flood watches and warnings. Currently the methods by which the decision to issue watches and warnings are under review. The EA is divided into eight regions, each with autonomy when it comes to procedures for flood forecasting. Each region receives rainfall forecast information from the Met Office in various formats, but each region uses this in different ways. A number of regions use a simple time-accumulation threshold (e g more than 20mm expected in 6 hours) as a basis for issuing warnings. There have been some moves to incorporate soil moisture deficit into the process, for example, but at present this has not been studied in depth.

Proposals from the meteorological community for probabilistic forecasts of rainfall based upon ensemble NWP model runs have been met with suspicion by some in the hydrological community (NERC, 2001). As yet the ensemble processing is not advanced enough to offer reliable probabilistic forecasts. There also needs to be a great deal of research into how such precipitation forecasts can be effectively presented to hydrologists and how they can be used in combination with hydrological models to provide indications of future flows and river levels.

This report presents an approach that represents the major contributing factors to developing extreme flood situations in an intuitively obvious way that can be rapidly assessed, accessed and updated. The authors suggest the use of a simple scoring system to give hydrologists guidance for deriving flood warnings. In doing so we attempt to represent the variety of contributing factors to floods. This is seen as a first stage framework for the decision support system and possible developments are discussed at the end of the paper.

Flash floods arise as a consequence of heavy rainfall falling upon a rapid response natural or artificial drainage basin. Whilst the characteristics of a basin govern the specific location, timing and depth of flooding, the amount and distribution in space and time of rainfall are prime factors in determining whether flooding is likely to occur at all.

Since by their nature flash floods occur very rapidly after the occurrence of rainfall, it is not usually sufficient to measure the rainfall in real time in order to attempt a flow forecast. Even extreme floods that occur some time after the rainfall, and may be monitored using upstream measurements of flow, demand the maximum lead-time possible to instigate disaster preparedness procedures. Hence, the availability of quantitative precipitation forecasts (QPFs) are therefore central to any operational procedure generating warnings of such events.

During the 1960s and 1970s rainfall forecasting procedures based upon the extrapolation of radar echoes were developed. Wilson et al (1998) discuss such work, noting that the accuracy of these forecasts generally decreases very rapidly during the first 30 minutes of a forecast because of the very short life-time of individual convective cells. However, more organised features such as cold front convection, squall lines and major thunderstorms, may persist for many hours and increased lead times using extrapolation may be possible in these circumstances (see, for example, Wilson, 1966, Browning et al, 1982). Nevertheless, there remains a rapid decrease of accuracy over the first three hours of an extrapolation-based forecast. Much of the problem, as pointed out by Wilson et al (1998), lies in our inadequate knowledge of the life cycles of convective cells and a lack of suitable observations to precisely forecast the initiation and dissipation of cells.

Unsuccessful efforts have been made to identify physical processes in the past history of the radar reflectivity pattern development which might be interpreted to allow forecasts of future cell development (Tsonis and Austin, 1981). However, Collier and Lilley (1994) suggested that it might be possible to develop a forecast system based upon the identification, from radar and satellite data, of the stage of development of systems using conceptual models. This has been exploited using object-oriented programming techniques by Hand and Conway (1995, see also Hand, 1996).

While this type of forecasting system has been developed for the operational forecasting of convection, trials have shown that the formulation of the life cycle model with the object-oriented scheme is of central importance (Pierce et al., 2000). The development of convection from clear air, except where there is significant numerical weather prediction (NWP) model diagnosed convergence in the boundary layer, cannot be forecast. For this to be forecast it must occur on a scale that the NWP model can resolve and this scale requires model grid lengths of 1km or less, which are only achievable in non-operational cloud scale models at present. At these resolutions the assimilation of data is very problematic. Also, since the conceptual model used relies upon a cell stage history from previous model runs to predict the length and form of the life cycle applied to each cell, showers developing between successive model runs are excluded from the forecast cycle in the latest run. This implies a requirement for frequent radar scans and efficient model runs, which, in turn, can present a flood forecaster with an abundance of information at a critical time in the decision making cycle.

The problem of forecasting convection from clear air is problematic. In recent years improved understanding of the condition of the boundary layer likely to lead to convective outbreaks has been exploited using forecast procedures employing Doppler radar measurements in the clear air (Wilson and Schreiber, 1986, Mueller and Wilson, 1989, Wilson and Mueller, 1993). A knowledge based expert system, known as Autonowcaster, has been developed from this experience by the National Center for Atmospheric Research (NCAR) in the USA (Wilson et al, 1998) and has met with significant success. However it has become clear that even small variations in boundary layer moisture are critical in deciding whether storms are formed or not (see, for example, Crook, 1996, Weckworth et al., 1996). Consequently it has been suggested by Mueller et al. (1993, see also Collier and Lilley, 1994) that monitoring cumulus cloud location and growth could provide a rough estimate of stability which might be used as a proxy for high resolution moisture observations.

Most previous methodologies have concentrated almost exclusively on atmospheric conditions and have not linked these meteorological forecast procedures into hydrological processes to provide an end to end system of flood forecasting. Opitz et al. (1995) describe practical methodologies used in the Eastern US for operational flash flood forecasting. In particular they show an ‘excessive rainfall checklist’ which includes atmospheric indicators of convective potential as well as antecedent precipitation and available precipitable water. Other decision tree and support systems such as Doswell (1986) and Colquhoun (1987) have been developed for more specific instances and have not been linked explicitly to a range of surface conditions that contribute to the flood process. The system advocated herein puts an equal weighting on both the atmospheric and hydrological aspects of the flood. This does not negate the possibility of using a more complex decision support system nested within such a scheme to gauge potential rainfall more accurately.

5.2 Seeking improvements to the recognition of extreme flood events

The uncertainties and difficulties noted in the previous section have led some researchers to believe that the way forward likely to meet with the most success is to use very high resolution numerical models with comprehensive data assimilation procedures incorporating new forms of remotely sensed data including that from radar. This is an attractive pathway and empirical ways of doing this have met with encouraging results (Krishnamurti et al, 1988, Jones and MacPherson, 1997), which, when linked to improved physical parameterisations of moist processes (eg prognostic cloud schemes and improved model resolutions) has resulted in better forecasts.

Unfortunately, it is highly unlikely in the near future that small mesoscale precipitation features can be located accurately within assimilation analyses however optimal and flexible they become. Similarly model forecasts will not be able to accurately locate future convective cloud. To do so would require a model having a grid length of 100m x 100m, and a highly accurate specification of initial conditions. This is not to say that there will not be improvements to forecasts on scales of tens of kilometres, but it is unrealistic to expect forecasts to be quantitatively accurate enough for operational use in very small river basins or urban drainage systems for extreme events. Such a view is supported by numerical experiments carried out by Gollvik (1999) who found that the small-scale precipitation produced in high resolution (~5km) numerical forecasts resulted in negligible extra skill compared with forecasts made using lower resolution (22km).

How then to proceed towards procedures useful for extreme flood forecasting? One way is to generate forecasts which are presented in probabilistic terms. Smith and Austin (2000) develop this approach using the fractal characteristics of rainfall. An alternative approach is to assess the likely accuracy of a set of specific forecasts from the predictions of river flow generated by inputting them to a specific hydrological model. In this approach it is always assumed that the rainfall forecasts may be in error.

Developments within the Met Office include those by Hand (2001), who has instigated a scheme which uses numerical model surface level fields along with land use and orographic data to generate probabilistic maps of convective rainfall at lead times of up to 36 hours. The use of this product as an operational aid to hydrologists has yet to be investigated.

The forecast hydrograph must be assessed in order to arrive at a consensus conclusion that is likely to be correct within defined bounds. To do this we need to understand how the characteristics of the rainfall time series engage with catchment conditions to give rise to particular flow characteristics. For example, heavy rain falling on a catchment having a large soil moisture deficit (SMD) is unlikely to produce large river flows unless the catchment surface is frozen or baked hard causing water to run off rapidly. Peterson et al (1999), in discussing a flash flood near Fort Collins, Colorado in 1997, note that several spatial and temporal features of the precipitation were highly relevant to the resulting flood. In particular, the final period of heavy rain developed over already saturated ground and the main rain area became quasi-stationary with convective core areas of 1-2km diameter continuously forming and moving down the Spring Creek drainage channel. A similar scenario occurred during the floods in England and Wales during the Autumn of 2000, although in this case ground saturation was maintained by a sequence of frontal systems (EA, 2001). There are a range of conditions leading to flash floods even within the same precipitation type. For example, Yarnal et al (1999) discuss four different types of mesoscale convective systems leading to flash floods in Pennsylvania.

5.3 Assessing the likelihood of extreme floods

The following are the catchment characteristics and precipitation conditions which need to be considered in assessing whether a rainfall event may lead to flash flooding in a specific catchment:

1. The likelihood that the heavy rain area will become stationary and long-lasting.
2. Availability of significant precipitable water in the lower atmosphere.
3. The likelihood that heavy cells embedded in the main area will move parallel to the main watercourse. If this happens the flood peak is likely to be enhanced.
4. The steepness of the catchment leading to a short time to peak.
5. The soil moisture condition of the catchment.
6. The likelihood of unimpeded flow to the main watercourse; whether or not significant vegetation and channel debris are likely to be problematic and whether or not there are constrictions in the channel that will facilitate a build-up of water for later release as a ‘wave’.
7. Snowmelt.

Points 1 to 3 are meteorological, although the importance of the cell velocity requires knowledge of the orientation of the watercourses. Points 3 to 6 depend on the catchment morphology. Whether debris has accumulated in the drainage channel causing local damming needs to be assessed using past experience embodied in an objective model. Other parameters may be derived from a digital terrain model (DTM).

Unfortunately, assessing whether a precipitation system is, or will become, stationary is difficult. Moncrieff and Miller (1976), Wilson and Megenhardt (1997) and others have shown that the initiation, organisation and life-time of convective storms is dependent upon the relative motion between the clouds and the convergence line causing the storms. The low-level wind shear directed normal to the convergence line (ΔU) is highly correlated to the boundary later relative cell speed. Large positive values of ΔU (indicating wind speed increasing with height) indicate the initiation of long lasting, organised convective storms. However, whether cells move depends upon the movement of the convergence line initiating their development. Stationarity may result from mesoscale or orographic forcing or both. The Autonowcaster system (Wilson et al, 1998) includes procedures for detecting and extrapolating convergence lines using Doppler radar data and NWP model output. This works well where convergence lines can be detected in the clear air.

Perhaps a more pragmatic approach is to continuously integrate radar reflectivity data throughout an event. This provides an early warning of stationarity, whilst also indicating the general direction of cell tracks and cell splitting. It is necessary to put all the factors above together to assess the likely spatial and temporal distribution of rainfall and soil moisture within the specific type of meteorological event that is going to occur.

If hydrological models exist for specific catchments then the data contained in Table 6 may be used to assess the likelihood of an extreme flood should a system of one of the types shown be likely to occur. In many cases in the UK parameters that represent gross properties of specific catchments are readily available in the Flood Studies Report (FSR, 1975) and Flood Estimation Handbook (2001). In this work the authors make use of this data, firstly to design a scoring system and then to test it.

5.3.1 An Objective classification of the likelihood of extreme floods

Whilst the parameters listed in the previous section are thought to be useful in assessing the likelihood of extreme floods, they only become so if their continuous and objective evaluations are updated in real time. Such updated forecast information can serve as a decision support tool to Flood Forecasting Officers, who are often under pressure at critical times. The decision support methodology developed in this study can play a complementary role in flood forecasting practices. In fact, such a methodology already exists in the Agency in the form of a decision making aid but on an ad hoc basis. However, this study offers a formalised procedure for the development of a decision aid table for the recognition of extreme events.

One simple approach to providing the guidance required is to associate an importance level on a scale of (say) zero to four to the answers for each question noted in section 3. A similar approach has been advocated by Colquhoun (1987) for thunderstorm and tornado forecasts. The total score indicates the likelihood of extreme flooding from a rainfall event of a particular type so identified. The magnitude of the score relates to the likely severity of the flood event defined in terms of the area covered by the flood, the duration of the event and the area inundated. For hydrologists using scores that are updated at regular intervals, and as the event moves from pre-rainfall into the rainfall phase, then a trend of increasing score may also act as a signal of increasing *(likelihood of)* severity.

The scoring methodology described above is but one possibility, which attempts to develop a system that can be used for different types of events and throughout the lifetime of an event. However, in the absence of more sophisticated models for flood forecasting, it may be more logical to separate the event into different stages and provide different scoring systems for each stage. This would reflect the changing influence and importance of the various factors affecting flood potential at different stages of an event's development. To be easily applicable to a forecasting hydrologist the scoring systems should be mutually consistent in that when one moves from one regime to another there is no discontinuity in the form of the information generated (i.e. the score should be on the same scale and the factors of importance graded consistently and clearly).

We present here an initial attempt at a system that can be used at all stages of an event and continuously monitored and updated

5.3.2 Baseline susceptibility to flooding

One can identify in the invariant morphological components of a catchment a baseline susceptibility to flooding. The simplistic approach undertaken here is partly analogous to the simplest varieties of lumped hydrological models. In these (see, for example, Shaw, 1994) the peak flow (Q_p in m^3s^{-1}) is related to the time to peak of the stream flow for small catchments such as those likely to suffer from flash flooding. This is in turn related, by empirical formulae, to the mean catchment slope (S in m/km), catchment area (A in km^2) and the length of the main stream channel (L in m) by

$$Q_p = \frac{0.22RAS^{0.4}}{0.00025L^{0.8}} \tag{1}$$

where R is the total mean catchment rainfall in mm.

The peak flow can then be seen to be approximately proportional to the ratio between the catchment area and the stream length and therefore provides a justification for inclusion in our criterion table of a score for this parameter as a proxy for the dependence upon the relatives size of the catchment compared to the stream capacity. One could postulate an even stronger dependence upon stream length (justifying the loss of the 0.8 power) if one wraps up the network routing parameter into this also. However, the coefficients in equation (1) are first approximations applicable to extreme flows observed in England and Wales.

This approach is useful for those catchments which do not have flood forecasting models implemented. An alternative approach where models such as equation (1), or more complex equations, do not exist, is to use the point scoring system to select input rainfall series, as discussed earlier, or to use the system as a decision support tool to alert the forecasting team for the onset of an extreme event. It this approach that we explore in what follows.

Many of the catchment characteristics can be related to and quantified by the descriptors defined in the Flood Estimation Handbook (FEH, Institute of Hydrology, 1999). The Flood Estimation Handbook (FEH, Institute of Hydrology, 1999) details values of descriptors for 943 catchments in the UK. For example one can refine soil type to the important parameter, that of standard percentage runoff (or SPRHOST as defined in the FEH, where the soil type is that found in the HOST data set (Boorman et al., 1995)).

In addition, catchment slope (DPSBAR), the extent of urban and suburban land cover (URBEXT) and the ratio of catchment area (AREA) to mean drainage path length (DPLBAR) are specified in the FEH. The latter may be regarded as a measure of channel capacity as a function of the stream routing network. Table 6 has been constructed incorporating these parameters as they relate to the catchment characteristics and precipitation conditions associated with extreme events. The parameter values have been derived from consideration of historic floods in a wide range of catchments.

Figure 17 shows the base assessment level derived from Table 6 for catchments in North West England. The definitions of high, medium and low susceptibility are given in the legend to this figure. These definitions have been derived on the basis of an assessment of the maximum likely score that a catchment may achieve without considering the precipitation input i.e. just using a morphological assessment. The assessment level is, as it should be, higher for those catchments with shorter time to peak. The five catchments shown to have a high susceptibility all have greater than 37% runoff either because they are very steep catchments, or are highly urbanised. We have not considered catchment wetness here as we assume that this factor will be assessed separately in deciding whether a major flood actually occurs (see later).

Krzysztofowicz (2001) makes the case developing hydrological forecasts in probabalistic terms. He defines "predictive probability" as a numerical measure of the "degree of certitude” about the occurrence of an event, conditional on all information utilized in the forecasting process. The predictive uncertainty evolves in time. In the next section of this paper we use the scoring scheme in Table 1 to assess the likelihood of a major flood event using a number of historic case studies. The analysis is then developed to provide a predictive probability measure as a function of score in order to provide a methodology for operational use in assessing the likelihood of extreme flood occurrence.

5.4 Tests on historic flood events

To test the validity of the scoring system developed in the last section as a contribution to decision support procedures we have evaluated the assessment levels from Table 6 for a number of historic extreme rainfall events occurring in England and Wales and reported in the literature. Some of these extreme rainfalls led to flooding, whilst others did not. In some cases the mean catchment rainfall is estimated. Each event comprises of evaluations using Table 6 for a number of individual rivers lying in the general area of heavy rainfall. The results are shown in Tables 7 to 11.

Figure 18 shows the probability of flooding as a function of the catchment area/DPLBAR, the approximate channel capacity, derived for the cases in Tables 7 to 11. Where the same score has been associated with several different values of the channel capacity, the mean value of channel capacity has been taken. The maximum probability (1.0) is derived as equivalent to the maximum score derived from Table 1 assuming strictly independent parameters (24) and no precipitation input. Some parameters are not independent, for example in an extremely urban area soil moisture is irrelevant. This relationship can be used directly to associate a probability of extreme flooding for an ungauged catchment, or in association with a deterministic model flow prediction. The curve shown in Figure 18 should be regarded as the envelope for extreme flooding. Probabilities (scores) beneath this envelope may still indicate flooding, but not flooding of an extreme nature. It is interesting to note that higher probability values seem to be associated with smaller and larger catchments, although further analysis is required to investigate the implications of this finding and relate it to other morphological catchment characteristics. Certainly small values of Area/DPLBAR are associated with steep catchments. Figure 18 is only consistent with equation (1) if the peak flow is related to channel capacity. The probability of extreme flooding was not found to be a function of catchment slope (DPSBAR).

The cases are selected for the varied nature of their extreme rainfall and the accessibility of information regarding the event. In each case the event occurs in the summer. This is typical for England and Wales and means that for these types of event the consideration of snow depth and melt can be neglected.

5.4.1 Walshaw Dean – 19 May 1989

The event at Walshaw Dean (sometimes referred to as the Halifax storm) resulted in a rainfall total of 193mm which fell in a period of about 2 hours (Acreman, 1989, Collinge et al, 1990, Collier and Hardaker, 1996). The catchments affected were mostly peat areas drained by a network of small brooks (becks). Damage was caused due to erosional effects in the upland areas and flooding occurred in culverted streams that ran through towns including Halifax. Damage was limited due to the natural condition of many of the streams, and the unpopulated nature of the catchments. There is also a suggestion that the presence of reservoirs mitigated the flow. Once the flow reached the River Calder the effect was reduced by the size of the channel relative to its catchment and damage in the town of Halifax was not substantial. The scores suggest that extreme flooding of Hebden Water and Hebden Beck is highly likely with flooding of the Calder somewhat less likely.

5.4.2 Sleaford – 23 September 1992

The 'Sleaford' Storm of 22-23 September 1992 was a widespread event with heavy rainfalls in a number of areas (Pike, 1993). Although the peak daily rainfall of 113mm was recorded at Sleaford in Lincolnshire, flooding occurred at a number of locations further south which experienced lower totals, but in shorter periods. By the categorisation of Bilham (1935) this was not an extreme event and did not result in severe damage.

This was a widespread event and offers the opportunity to study the varying effects on different rivers that experienced the effects of this storm. A selection of scores for a variety of rivers is shown in table 8. This storm appears to have been a widespread double-frontal event with some embedded convective elements. The flooding effects of this storm were mitigated by low soil moisture contents resulting from a period of very low rainfall prior to the storm. In this case the scores suggest that the Silk Stream is very susceptible to flooding. Flooding is also likely for the Great Ouse, but is somewhat less likely on the Tove, and probably unlikely on the Pang.

5.4.3 Chew Stoke - 10 July 1968

On 10 July 1968 there was heavy rain over a large area stretching in a band from the Bristol Channel to Lincolnshire. The heaviest falls of 175mm were recorded at Chew Stoke in Somerset and resulted in flooding on the Chew (Salter, 1968). There was significant flooding in the village of Cheddar and the event was responsible for 6 deaths and considerable damage. This event illustrates the importance of determining the catchment over which the really extreme rainfall was taking place. The storm in this case came in from the west and it is likely that some funnelling of the system took place along the steep sided Cheddar Gorge and concentrated rainfall in this valley (Hanwell and Newson, 1970). Certainly appears that the alignment of the channel with the direction of motion of the storms provided a greater risk of flooding on the Chew than was experienced on the neighbouring Frome and Midford Rivers. The scores in Table 9 indicate the expectation that severe flooding would indeed occur on the Chew and the Brue, but somewhat less severe flooding would occur on the Frome and the Midford.

The storms moved relatively quickly, but regeneration of cells took place repeatedly ahead of a warm front over the same areas. There were very heavy falls recorded across England in a band stretching from Somerset to Lincolnshire, but the worst floods and destruction took place in a small number of gorges on the north side of the Somerset levels.

5.4.4 Lynmouth – 15 August 1952

The flood at Lynmouth in Devon on 15 August 1952 remains one of the most devastating flash flood events in British history. It was also a case of extreme rainfall with values of 228mm recorded within a 12 hour period. This was a truly exceptional event, with a vast quantity of rain falling over a prolonged period in several bursts. This followed a period of wet weather in the previous two weeks, so that, although there are no records of soil moisture deficit, one can conclude that it was very small (Marshall, 1952).

The Lynmouth storm illustrates the difficulty in assessing stationarity of storm cells at a particular location. The 700mb ‘steering level’ winds from Larkhill (the most appropriate sounding available) were 24kt at 1400. But the storms did not propagate away from the Lyn catchment but repeatedly redeveloped in this locality (Bleasdale and Douglas, 1952).

The steepness of the East and West Lyn catchments flowing off Exmoor contributed to a number of flood waves proceeding down either branch of the river. However, the major factor in the exacerbation of the flood and causing such devastation was the build-up of debris against old stone arch bridges which constricted the channel. This produced a series of temporary dams which burst under the pressure of later exceptional flows. Although greater rainfall totals were recorded over the Barle and Exe valleys, the combination of the steepness of the Lyn, the availability of debris material and the channel constrictions was critical in creating the destructive flood.

The scores for this storm were very high (Table 10). There is a clear difference between the scores for the Lyn catchment and those of the Barle and Exe. These latter rivers actually received greater rainfall, but due to their size and less steepness they did not experience the same damage as the Lyn.

5.4.5 Hampstead – 14 August 1975

The storm at Hampstead of 14 August 1975 produced a peak rainfall of 170.8 mm in a 2 hour period in an urban area of Central London (Keers and Wescott, 1976). The extreme rainfall was concentrated over a small area, but being urban the runoff from this area was rapid and caused deaths and other disruption. Evidence suggests that the storm remained stationary due to a strong surface convergence pattern, and that the local topography centred the rainfall maximum over the higher ground of Hampstead. The high scores (Table 11) for this storm reflect the stationary nature of the event and the urban character of the catchments. Scores greater than 20 indicate that a major flood is likely.

5.4.6 Discussion

It is apparent that the scoring system identifies the more damaging events. Scores greater than 30 indicate the likelihood of extreme floods, and scores between 20 and 30 indicate major floods. However, scores less than 15 indicate a situation in which floods are unlikely. The highest score observed for this range of tests goes, not to the most intense rainfall event, but to that where circumstances combined to produce the worst flood. For this limited number of case studies (with some deficiencies in the data), the system appears to perform better in giving higher scores to the more destructive events, even when similar rainfall during an event produced different results in a variety of catchments.

There is clearly a difficulty in deducing all the scores required to complete these tables fully. For historic events, observations of soil moisture and atmospheric conditions were not always available and this can remain the case to this day. This situation would be analogous to a real-time forecast where one would not expect to have accurate observations of every variable one would ideally like. Therefore, it would be more consistent to present a percentage score graded out of the maximum number of parameters judged (one could also impose a minimum number of parameters required in order to limit uncertainty).

	Assessment level				
	0	**1**	**2**	**3**	**4**
Steep catchment? (DPSBAR)	<1:50 (<0.02)	1:50 - 1:20 (0.02-0.05)	1:20 - 1:10 (0.05-0.10)	1:10 - 1:5 (0.10-0.20)	>1:5 (>0.20)
Land use/Veg. Type (URBEXT)	Essentially Rural <0.05	0.05 – 0.125	0.125-0.250	0.250-0.5	Extremely Urban >0.5
Snow depth	0mm	<10mm	10-50mm	50-100mm	>100mm
Debris?	No dry spell - fast flow	No dry spell - slow flowing river	dry spell before - slow flowing rural or fast urban	short dry spell - urban med to slow flow	Long dry spell before - urban med. to slow flow
SMD	>100mm	50-100mm	15-50mm	5-15mm	<5mm
Channel constrictions	None	Some constrictions	Soft constrictions	Solid constrictions or soft ones that may act temporarily	Major, solid constrictions
Heavy Rain? (Peak hourly catchment rainfall)	<4mm/h	4-10mm/h	10-20mm/h	20-40mm/h	>40mm/h
Long lasting?	v.short <15 mins	short 15-45 mins	medium 45-90 mins	long 90-180 mins	v.long >180 mins
Rain stationarity	Rapid >20m/s	Fast 10-20m/s	medium 5-10m/s	slow 1-5m/s	Stationary <1m/s
Direction of motion	80-90 degs	60-80 degs	20-60degs	5-20 degs	0-5 degs - parallel
AREA/ DPLBAR	8-14 km^2/km	14-30 km^2/km	5-8 km^2/km or >30km^2/km	1-5 km^2/km	<1 km^2/km
Percentage Runoff (SPRHOST)	<10	10-19.9	20-34.9	35-50	>50

Table 6: Decision support scoring system for use prior to the onset of rain.

	River		
	Hebden Water	**Hebden Beck**	**Calder**
DPSBAR	0.12	0.10	0.11
URBEXT	0	0	0.0856
Snow depth	0	0	0
Debris?	Yes	yes	some
SMD	n/a	n/a	n/a
Heavy Rain?	100	70	3
Direction of Motion	300-270=30	360-300 = 60	300-260=40
Rain Stationary?	Yes	Yes	Yes
Long lasting?	120 mins	120 mins	120 mins
Channel Constrictions	Yes (solid culverting)	n/a	Some
AREA / DPLBAR	36.0/5.39	22.25/6.04	905.16/43.10
SPRHOST	56.3	57.4	30.1
Score	**25+**	**25+**	**18+**

Table 7: Decision support scoring system for Walshaw Dean Storm, 19/05/89.

	River			
	Silk Stream	**Pang**	**Great Ouse**	**Tove**
DPSBAR	0.04	0.05	0.03	0.04
URBEXT	0.2978	0.0045	0.0217	0.0065
Snow depth	0	0	0	0
Debris?	Prior drought	Prior drought	Prior drought	Prior drought
SMD	Prior drought >50mm	Prior drought >50mm	Prior drought >50mm	Prior drought >50mm
Heavy Rain?	20mm/h	20mm/h	28mm/h	38mm/h
Direction of Motion	230	250	245	n/a
Rain Stationary?	Light to Moderate Winds	Light to Moderate Winds	Light to moderate winds	Light to moderate winds
Long lasting?	13 hrs	13 hrs	16 hrs	16 hrs
Channel Constrictions	Urban drainage	No	Some	yes
AREA / DPLBAR	28.24/5.33	175.49/20.68	1470.12/90.81	133.2/12.23
SPRHOST	50.3	22.0	39.9	41.2
Score	**26**	**14**	**20**	**18**

Table 8: Decision support scoring system for Sleaford Storm, 22-23/09/92.

	River			
	Chew	**Brue**	**Frome**	**Midford**
DPSBAR	0.05	0.07	0.03	0.08
URBEXT	0.0089	0.0065	0.0713	0.0301
Snow depth	0	0	0	0
Debris?	n/a	n/a	n/a	n/a
SMD	17	23.4	22.9	22.1
Heavy Rain	50mmh^{-1}	20mmh^{-1}	25mmh^{-1}	35mmh^{-1}
Direction of Motion	270-85=185	270-70=200	270-180=90	270-180=90
Rain Stationary?	15ms^{-1}	15ms^{-1}	15ms^{-1}	15ms^{-1}
Long lasting?	9 hours	5 hours	5 hours	5 hours
Channel Constrictions	Some	Some	Some	n/a
AREA / DPLBAR	129.1/15.42	139.52/ 13.46	150.61/ 13.17	147.4/13.76
SPRHOST	28.9	36.4	43.5	29.1
Score	**22**	**19**	**16**	**17**

Table 9: Decision support scoring system for Chew Stoke Storm, Bristol, 10 July, 68.

	River			
	East Lyn	**Barle**	**Exe**	**West Lyn**
DPSBAR	(0.09)	0.14	0.15	0.30
URBEXT	0.0004	0.0004	0.0001	0.0004
Snow depth	0	0	0	0
Debris?	Yes	No	No	Yes
SMD	~5mm	~5mm	~5mm	~5mm
Heavy Rain?	141mm	203mm	170mm	149mm (228mm)
Direction of Motion	160-157=3	300-157=143	280-157=113	180-157=23
Rain Stationary? (700mb wind)	$7ms^{-2}$	$7ms^{-2}$	$7ms^{-2}$	$7ms^{-2}$
Long lasting?	10 hours	10 hours	10 hours	10 hours
Channel Constrictions	Yes	No	No	Yes
AREA / DPLBAR	76/12.0	128.01/21.81	120.87/26.49	23.5/9.2
SPRHOST	(24.8)	42.8	34.6	24.8
Score	**30+**	**28**	**27**	**38**

Table 10: Decision support scoring system for Lynmouth Storm, 15/08/52

	River		
	Brent	**Dollis Brook**	**Silk Stream**
DPSBAR	0.04	0.05	0.04
URBEXT	0.3973	0.2525	0.2978
Snow depth	0	0	0
Debris?	n/a	n/a	n/a
SMD	n/a (Urban)	n/a (Urban)	n/a (Urban)
Heavy Rain?	10	30	70
Direction of Motion	0 (040)	0	0
Rain Stationary?	Yes	Yes	Yes
Long Lasting	180 mins	180 mins	180 mins
Channel Constrictions	Urban drainage	Urban drainage	Urban drainage
AREA / DPLBAR	115.85/9.22	23.76/6.33	28.24/5.33
SPRHOST	49.7	50.5	50.3
Score	**24**	**30**	**30**

Table 11: Decision support scoring system for Hampstead Storm, 14/08/75.

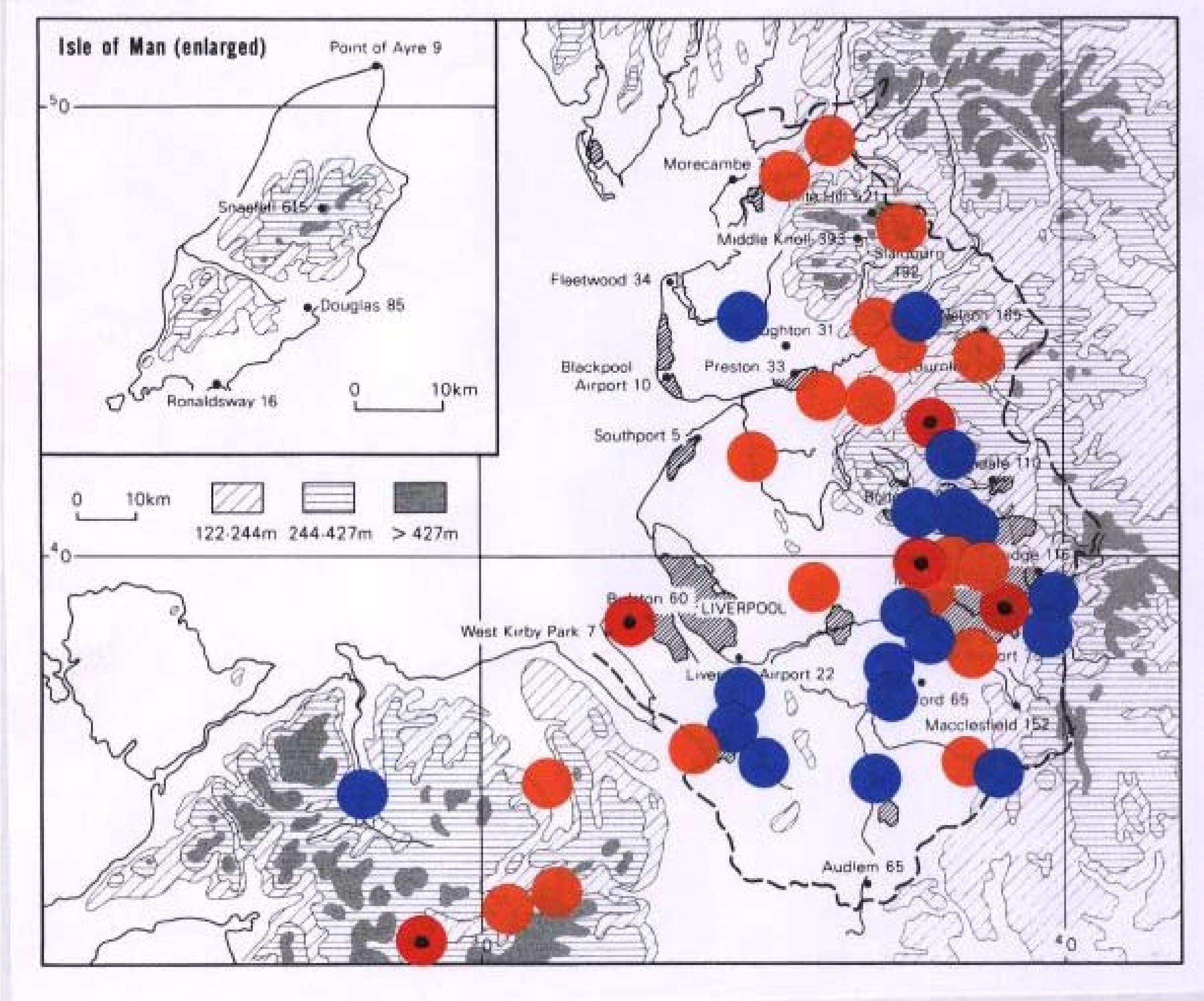


Figure 17: Baseline susceptibility of catchments in NW England to severe flooding: Red circles with a black dot - high susceptibility (score 9-10); Orange circles - medium susceptibility (score 7-8); Blue circles - low susceptibility (score less than 7). Also shown is the topography of the area giving locations of some town and their altitudes (in metres). Coordinates are national grid references.

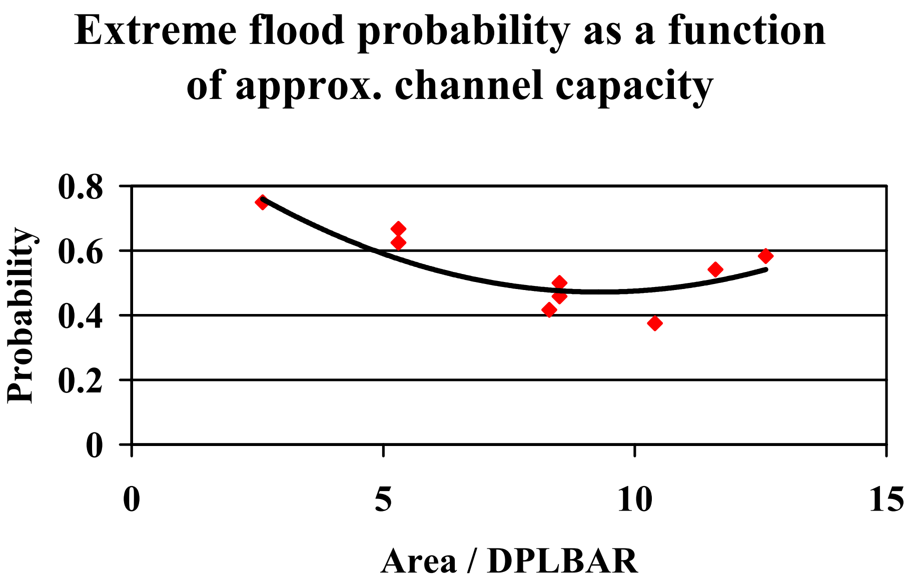

Extreme flood probability as a function of approx. channel capacity
Probability
0.8
0.6
0.4
0.2
0
0
5
10
15
Area / DPLBAR

Figure 18:

6. CONCLUSIONS

The need for a rapid assessment of the likelihood that a hydro-meteorological event will lead to extreme flooding is recognised by operational Flood Forecast Officers in the UK and elsewhere. A methodology for recognising extreme rainfall and flood events based upon a conceptual model of causal meteorological conditions and upon a question and answer assessment procedure has been proposed, and partially tested, in this paper. It is recognised that further analysis on a wider range of events would provide a sounder basis upon which to base the procedure. It would be straightforward to implement this approach in a computer based system, although it is recognised that further work is necessary to identify the most important key questions and answers that have to be addressed regarding the flood forecasting element.

The implications of the analysis of extreme rainfall events for estimates of Probable Maximum Precipitation have been discussed. Whilst the estimates of PMP provided by the FSR appear inadequate, those inferred by extrapolating the FEH seem to be overestimates. Given the importance for engineering design of PMP it is necessary to undertake further work to clarify the situation.

It is accepted that quantitative precipitation forecasts are never likely to be 100% accurate and reliable. Extreme events are always likely to be very difficult to recognise, and yet it is these events that need to be forecast reliably. Limitations in NWP models and observing systems will inevitably limit our ability to forecast such events and therefore decision support systems are needed to aid those who have to make key decisions at critical times under pressure. Hence the importance of recognising antecedent conditions leading to these events is paramount in operational systems.

7. TRAINING DATA SETS

The extreme flood events discussed in the previous section provide an opportunity to construct rainfall time series which can be used to test operational hydrological models and procedures. Such datasets are given in Appendix A, and represent conditions which have occurred, and which will occur somewhere in England and Wales in the future. It may be possible to develop from these data a radar-type gridded dataset of a consolidated extreme event. A starting point might be the Walshaw Dean storm as good radar data are available for this storm. The product so-produced could be used to aid hydrological model development.

8. RECOMMENDATIONS AND PROPOSALS FOR FURTHER WORK

(1) New events should be routinely analysed and tested to see how they fit into the diagram shown in Figure 14, and the conceptual model shown in Figure 15 if they are frontal, which should both be updated if necessary.

(2) Met Office Mesoscale Model (MM) NWP outputs can be used to provide details of the synoptic evolution, expected rainfall intensity, accumulation and distribution, updated four times a day. If the forecast outputs from the model

suggest that rainfall amounts could be high according to pre-defined criteria, then the forecast could be refined into a warning of possible amount and duration of extreme rainfall by identifying the category of the expected rainfall producing system.

Categorization would involve:-

(a) Picking out threatening orographic events using the criteria in this report.

(b) Identifying slow moving frontal zones (particularly warm occlusions or warm fronts) with high precipitation rates and the presence or not of embedded instability.

(c) Identifying regions lying close to (within 200 Km, say) and to the north and west of the centre of a slow moving depression.

(d) Identifying regions of showers (embedded in frontal zones or otherwise) with high rainfall rates/accumulations from the MM. Then identifying those that are likely to produce large damaging hail and/or likely to possess multicell characteristics in areas of potential instability, which if released, would produce large amounts of CAPE. The Met Office Gandolf, Nimrod and CDP systems all have methods of determining these criteria, which could be utilised, perhaps probabilistically.

A joint Defra/Met Office/EA project should be set up with a view to establishing a prototype 24-hour early warning system to be tested on independent data, which should include non-extreme as well as extreme events.

(3) Recent work at the University of Salford (Sleigh and Collier, 2002) proposes a new method of identifying extreme convective events based upon an analysis of vorticity. This method should be investigated further using MM NWP, and, if possible Doppler radar data. Such work could be carried out as part of the project proposed under (2) above.

(4) A scoring system for river catchments developed during the Project to provide an indication of the extreme flood potential. By using the scoring system that identifies the contributions to a flood event from the variety of components it is also possible to update and readily comprehend. The methodology is capable of formalising intelligence tables often developed by flood forecasting and warning teams in the Environment Agency using their local knowledge but on an *ad hoc* basis. Such a scoring system can be used as a decision support tool by practitioners. It is recommended that clear guidelines be developed by studying a wider range of events covering a wider area of the country, and identifying the significance of the score values. The system could also be used to identify the impacts upon the flood response of a catchment due to environmental change (such as climatic or land use change). Further work is proposed to develop the envelope curve proposed as an assessment tool.

(5) The training data set given in Appendix A should be combined with radar data from an extreme event (e.g. the Walshaw Dean storm) to develop a gridded data base for use in hydrological model development.

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Appendix A: Training datasets for input to hydrological models for a range of extreme rainfall events

Below are duration/depth tables for a few events. The category refers to the regions on Fig 14.

- Duration/depth **Lynmouth 15/08/52** Total 228mm in 12 hours. Category D (Frontal with embedded convection or MCS)

  (Derived using data from British Rainfall but mostly from information in Bleasedale and Douglas, Met. Mag. Dec 1952, note the observed lull T+5 to T+6)

Time into event (h)	Depth (mm)
1	11
2	23
3	34
4	52
5	70
6	78
7	100
8	141
9	182
10	205
11	216
12	228

- Duration/depth **Martinstown 18/07/55** Total 280mm in 15 hours. Category D (Frontal with embedded convection)

  (Derived using data and eye-witness accounts from British Rainfall, note observed lull T+5 to T+7)

Time into event (h)	Depth (mm)
1	30
2	70
3	110
4	150
5	200
6	204
7	208
8	228
9	248
10	270
11	274
12	276
13	278
14	279
15	280

- Duration/depth **Hampstead 14/8/75** Total 171 mm in 3 hours. Category A (Severe convection/multicell)

  (Derived using scaled Parliament Hill data. Estimated that Hampstead never exceeded a max. hourly rate of 125 mm/h. From Keers and Westcott, Weather 1976, pp1-10.)

Time into event (mins)	Depth (mm)
15	3
30	8
45	14
60	27
75	42
90	58
105	78
120	108
135	133
150	152
165	164
180	171

- Duration/depth **Halifax 19/5/89** Total 193 mm in 2 hours. Category A (Severe convection/multicell)

  (Estimated using a bell shaped profile which is consistent with eye-witness reports as in Acreman, Weather 1985, 44, No.11 pp 438-446.)

Time into event (mins)	Depth (mm)
15	20
30	45
45	72
60	100
75	130
90	155
105	175
120	193

- Duration/depth **Norwich 26/8/12** Total 186 mm in 22 hours. Category C (Frontal - low moving slowly north to east of region)

  (Derived using rainguage data from Ipswich Road published in British Rainfall 1912)

Time into event (h)	Depth (mm)
1	1
2	2
3	3
4	5
5	10
6	18
7	34
8	51
9	70
10	93
11	128
12	145
13	156
14	162
15	167
16	170
17	174
18	176
19	179
20	181
21	184
22	186

The following tables show estimated areal coverage (sq Kms) according to total rainfall depth (mm) for each event that could be estimated in each category referred to in Table 3. The average of all events is a rounded figure.

F	**26/08/12**	**26/09/15**	**22/07/30**	**12/08/48**	**Average**
25	68000	32000	15000	15000	*33000*
50	23000	12000	12000	7000	*13000*
75	10400	9400	8000	3900	*7900*
100	2790	1200	3900	2080	*2490*
125	1870	690	2340	1300	*1550*
150	700	180	570	20	*370*
175	55	55	470	0	*145*
200	0	0	310	0	*80*
225	0	0	230	0	*60*
250	0	0	130	0	*35*

F***	**21/10/08**	**28/06/17**	**15/07/37**	**15/08/52**	**18/07/55**	**10/07/68**	**15/09/68**	**Average**
25	5000	31000	5200	6000	6000	66500	35000	*22100*
50	1040	14600	3300	1000	3000	32000	22500	*11100*
75	260	6200	1300	800	1500	11500	12500	*4900*
100	30	2100	100	400	820	2290	6250	*1710*
125	10	750	10	260	510	550	2350	*630*
150	5	240	0	110	350	80	570	*190*
175	5	75	0	80	215	0	90	*65*
200	0	35	0	45	125	0	15	*30*
225	0	5	0	5	75	0	0	*10*
250	0	0	0	0	35	0	0	*5*

C***	**19/08/24**	**25/06/35**	**04/08/38**	**Average**
25	1500	600	3000	*1700*
50	120	310	1800	*740*
75	70	65	550	*230*
100	35	10	420	*155*
125	25	5	130	*55*
150	20	5	20	*15*
175	10	0	0	*3*
200	7	0	0	*2*
225	3	0	0	*1*
250	0	0	0	*0*

C	**12/7/00**	**09/6/10**	**16/6/17**	**29/5/20**	**11/7/32**	**26/9/33**	**08/6/57**	**05/9/58**	**14/8/75**	**19/5/89**	**Average**
25	2600	5000	135	60	1200	700	1000	4700	110	225	*1600*
50	390	830	50	55	700	200	250	1850	55	20	*440*
75	160	140	10	50	130	55	110	390	30	1	*110*
100	50	30	5	40	55	20	70	25	15	1	*30*
125	0	5	0	0	10	1	50	5	5	1	*8*
150	0	0	0	0	0	0	40	0	1	1	*4*
175	0	0	0	0	0	0	25	0	0	1	*3*
200	0	0	0	0	0	0	15	0	0	0	*2*
225	0	0	0	0	0	0	5	0	0	0	*1*
250	0	0	0	0	0	0	0	0	0	0	*0*

The following table shows the average area (sq Kms) for each total depth (mm) for each rainfall category.

Category/ Depth	**F**	**F*****	**C*****	**C**
25	33000	22100	1700	1600
50	13000	11100	740	440
75	7900	4900	230	110
100	2490	1710	155	30
125	1550	630	55	8
150	370	190	15	4
175	145	65	3	3
200	80	30	2	2
225	60	10	1	1
250	35	5	0	0