1996
2006

Cumbria Floods Technical Report

Factual report on meteorology, hydrology and impacts of January 2005 flooding in Cumbria

enhancing... improving... cleaning... restoring... changing... tackling... protecting... reducing... **creating a better place...** influencing... inspiring... advising... managing... adapting...

ea/br/e/std/vr10thanni

Cover Photograph is obtained from www.bbc.co.uk/cumbria and is used with permission.

CONTENTS

Note: All times stated in this report are to GMT unless otherwise stated. Times are given in the 24hr clock.

Tables

Figures

Photographs

List of Appendices

This page left blank intentionally

Glossary

Afflux	Afflux is an increase in water level that can occur upstream of a structure, such as a bridge, at high (flood) flows.
Annual Exceedance Probability (AEP)	The probability of a flood event being met or exceeded in any one year. For example, a probability of 1 in 100 corresponds to a 1% or 100:1 chance of an event occurring in any one year; see also return periods.
Anticyclone	A system of winds rotating outwards from an area of high barometric pressure, producing fine weather.
Advanced Very High Resolution Radiometer (AVHRR)	A device carried by polar orbiting satellites providing visible and near-infrared imagery
AVM	Automatic Voice Messaging System is used to issue flood warnings. Now superseded by Floodline Warnings Direct
Catchment	A surface water catchment is the total area that drains to a river. A groundwater catchment is the total area that contributes to the groundwater component of the river flow.
Catchment Flood Management Plan (CFMP)	A large-scale planning document that identifies long-term sustainable policies for the holistic management of flood risks in a catchment.
Critical Ordinary Watercourses (COWs)	Stretches of non-main watercourses that have been defined as critical in terms of flood risk through consultation between the Environment Agency and Local Authorities. The definition is based on the number of houses at risk per kilometre of bank and environmental designations. COWs will become main river in three tranches, the latest took place in April 2006.
Dew Point Temperature	Dew point temperature is the temperature to which the air would have to cool in order to reach saturation. The higher the dew point temperature, the more humid the air.
Digital Terrain Model (DTM)	Digital terrain model used in soil moisture and hydrological models.
Field Capacity	Mass of water retained by a previously unsaturated soil when free drainage has ceased
Flood Warning Area (FWA)	A defined area within which the Environment Agency undertakes to provide a flood warning service
Fluvial	Pertaining to a watercourse (river or stream).
Gandolf	A short range precipitation forecasting (nowcasting) scheme run by the Met Office. It is a version of Nimrod which generates high resolution (2km, 15min) forecasts of surface rain rate and rainfall accumulation. The scheme possesses an enhanced capability to predict intense precipitation associated with severe thunderstorms.
Geomorphology	Processes of erosion, deposition and sediment transport that influence the physical form of a river and its floodplain.
GMT	Greenwich Mean Time; see also UTC
Isobars	Lines on a map which connect positions having the same atmospheric pressure at a given time or on average over a given period.
Main river	Watercourses defined under Water Resources Act 1991on a ‘Main River Map’ designated by Defra. The Environment Agency has permissive powers to carry out flood defence works, maintenance and operational activities for Main Rivers only. Responsibility for maintenance, however, rests with the riparian owner, namely the land owner.
Mesoscale	The scale appropriate for modelling and describing atmospheric systems, being approximately 12km in the Met Office meso-scale model, and 4km and 1km in high resolution versions.
MORECS	Met Office Rainfall and Evaporation Calculation System
MOSES	Met Office Surface Exchange System
Nimrod	The Met Office short range forecasting (nowcasting) model which generates quantitative precipitation forecasts at 5km horizontal resolution and at 15 minute intervals up to 6 hours ahead.
Nowcasting	Term used to describe current conditions at meso-scale using satellite and weather radar, together with a forecast up to 2 or 3 hours ahead based on extrapolation of current trends. Also used to describe the up to 6 hours ahead forecasts in Nimrod; see above).

Occlusion	A phenomenon in which the cold front of the depression overtakes the warm front, causing upward displacement of warm air between them.
Oktas	A unit of cloud cover, equal to one eighth of the sky.
Ordinary Watercourses	All watercourses not designated as Main River, COWs or IDB watercourses. The operating authority, local authority or IDB, has permissive powers to maintain them but the responsibility to do so rests with the riparian owner.
Orographic	Refers to forced uplift of air mass due to high ground. Orographic rainfall is rainfall which is caused or enhanced by uplift.
Radiosondes	A miniature radio transmitter which broadcasts information about pressure, temperature etc., from various levels of the atmosphere usually carried by a balloon.
Return period	The average length of time separating flood events of a similar magnitude: a 100-year flood will occur on average once in every 100 years; see also annual exceedance probability.
Site Controllers	Operational response for carrying out investigation into the incident, managing remedial measures to minimise any impact on the environment and undertaking any appropriate enforcement action.
Soffit	Underside of the deck of a bridge or roof of a culvert
Soil moisture deficit	The amount of rainfall required to restore soil to its field capacity; see also field capacity
Stage	Water level measured at a flow gauging station or similar. Usually with reference to a local datum.
Standard of Protection	The flood event return period above which significant damage and possible failure of the flood defence could occur.
Surcharged	In terms of bridges or culverts, this term means that the water level has reached the soffit
Surface Water Flooding	Surface water flooding is that which occurs from excess water that runs off across the surface of the land and does not come from a watercourse. There is very limited information available about flooding from this source.
Synoptic chart	Also known as ‘weather charts’ which show current weather on geographical charts with standardised symbology to represent weather features.
Telemetry	Equipment for recording the readings of an instrument (such as a rain gauge) and transmitting them via a telephone line to a central location. This is used extensively to allow Environment Agency offices to monitor river levels and rain gauges.
Tipping bucket rain gauge (TBR)	Rain gauge that collects small amount of rain, typically 0.2m, and tips and records time of tip.
UTC	Universal Time Co-ordinated is the preferred measure of time relative to its observation which has superseded Greenwich Mean Time (GMT) as the international standard time measure. In practical terms, UTC is the same as GMT
Wet-bulb temperature	The lowest temperature that can be obtained by evaporating water into the air at constant pressure.
Wrack	Debris left by flooding

Flooding and probability

Historically, the likelihood of a flood event was described in terms of its return period. For example, a 1 in 100 year event could be expected to be equalled or exceeded on average once every 100 years. However, there is a tendency for this definition to be misunderstood. There is an expectation that if such an event occurs, it will not be repeated for another 100 years. This is not the case; the key words in the above example are 'on average'.

To try to avoid the misunderstanding, we now generally express flood events in terms of the chance of them occurring in any year. This can be stated in two ways, namely a percentage or a probability. Taking the above example, we would say that this event has a 1 per cent, or 1 in 100, chance of being equalled or exceeded in any year.

Chance of being exceeded in any year (AEP)	Return period (year)
50%	1 in 2
20%	1 in 5
10%	1 in 10
4%	1 in 25
2%	1 in 50
1.33%	1 in 75
1%	1 in 100
0.67%	1 in 150
0.5%	1 in 200
0.2%	1 in 500
0.01%	1 in 1000

In this technical report, both the percentage chance and probability are used throughout the text. For clarity, return periods are only used in tables.

This page left blank intentionally.

1 EXECUTIVE SUMMARY

At 1530hrs on 6 January 2005, the Met Office issued a warning to the North West Region of the Environment Agency in respect of heavy rain over Cumbria and other areas. This was the first indication of one of the most significant floods to occur in England and Wales in the last few decades. The warning also included strong to gale force winds, which were to be a significant feature of the event.

The rainfall started over the mountains in Cumbria in the late evening and continued until about midday on 8 January. During this period, some rain gauges recorded over 200mm of rain. The heaviest rainfall extended in a band from the mountains of Great Gable and Scafell, across Helvellyn and the eastern Lake District, and across the Howgills into the Yorkshire Dales. The rain was caused by a strong airflow of unusually warm, moist tropical air, which was forced northwards ahead of an Atlantic cold front. Towards the end of the event, the rain was enhanced by strong frontal uplift and convection as a depression passed to the north.

The return period of the rainfall in Cumbria varied from less than 5 years (20%) to about 175 years (0.57%); the average was some 40 years (2.5%). The most extreme rainfall was over the high ground in central Cumbria where many gauges recorded rainfall with return periods in excess of 100 years (1%). The Met Office suggests a return period of about 100 years (1%) for the storm as a whole.

Flood Watches for all of Cumbria were issued on 7 January in response to the Met Office's warning. In response to the developing situation, the Environment Agency opened the flood incident room in their Penrith office at 0700hrs on 7 January and issued the first Flood Warnings around midday.

All rivers in Cumbria responded to the rainfall and the Rivers Eden, Kent, Greta, Eamont, Derwent and Cocker experienced their highest recorded flows. A flow of 1520m^3/s was recorded at the Sheepmount Gauging Station on the River Eden at Carlisle. This is believed to be the highest on the Environment Agency's archive of river flows in England and Wales. Its return period is estimated to be in the region of 175 to 200 years (0.57% to 0.5%). The flood level in Carlisle was at least 1m higher than any previous event since records began in 1771. The Rivers Caldew, Derwent, Greta, Petteril, Eamont, Irthing, Kent, Sprint and Mint all had flows with return periods in excess of 50 years (2%).

The first reports of flooding came during the evening of 7 January and many were as a result of surface water rather than the river system. This was particularly the case in Carlisle and Keswick. By the early hours of 8 January, significant flooding had commenced in Appleby, Cockermouth, Carlisle, Kendal, Keswick, Penrith and other locations. The first flooding from the rivers occurred in upstream locations, such as Appleby.

By 0600hrs, reports indicated that there were hundreds of properties flooded in Cumbria. By 0830hrs, the flood defences along the River Eden had overtopped and the Civic Centre and Police Station in Carlisle were flooded. The overtopping was due to high river levels rather than a structural failure of the defences. The situation was made worse by the storm force winds and rain which made many of the county's roads impassable.

At 0900hrs on 8 January, a strategic (Gold) level command centre was established at Cumbria Constabulary's headquarters in Penrith to co-ordinate the multi-agency response. This was supplemented by a tactical (Silver) level command centre at Carlisle Castle.

At 1045hrs, the Environment Agency issued Severe Flood Warnings for Carlisle. The formal evacuation of people in the city started shortly afterwards. At 1100hrs, a major power failure affected about 250,000 properties in Cumbria and Lancashire. In Carlisle, this was followed by the failure of parts of the telephone system at 1800hrs. The mobile system had already failed due to the loss of power.

The river levels peaked at varying times during 8 January. Amongst the first were the River Greta at Keswick and the River Kent at Kendal, which peaked at around 0200hrs. On the River Eden, the peak occurred at 0515hrs at Appleby and 1430hrs at Carlisle. The Environment Agency began to downgrade the Flood Warnings during the latter part of 8 January. Late the following day, the Environment Agency breached the Carlisle defences to allow floodwaters to drain away.

The flooding affected more than 2,500 properties in Cumbria. About three quarters of these were in Carlisle with the remainder principally in the towns of Appleby, Keswick, Kendal, Penrith, Eamont Bridge and Cockermouth. In terms of damage, it was one of the most significant fluvial floods in the United Kingdom during the last 50 years. The total damages are likely to be in the order of £500 million.

2 INTRODUCTION

2.1 Background

Heavy rain on 6, 7 and 8 January 2005 resulted in the highest ever recorded flows in the Rivers Eden, Caldew, Petteril and Kent. This caused extensive flooding throughout Cumbria and some 2,500 properties were affected. The flooding in Carlisle was the highest recorded since at least 1771 and unfortunately two elderly ladies died in their homes. Other towns affected were Appleby, Cockermouth, Kendal, Keswick and Penrith. Figure 2-1 shows the main rivers and the key locations.

The impact was made worse by the strong gales that accompanied the rain, which resulted in extensive power cuts.

2.2 Scope of the Study

The Environment Agency identified the need to produce a technical report on the flooding in Cumbria. The objective was to provide a comprehensive and definitive analysis of the event and its impact in terms of meteorology, hydrology, extent and damages. The Environment Agency commissioned Black & Veatch in late 2005 and Black & Veatch engaged the Met Office as sub-consultants for the meteorological aspects of the study.

Following the event, significant efforts were made to understand the flooding and improve flood risk management in Cumbria. This has resulted in a large number of reports and other documents being available. The principal ones are those which examine the flooding at a particular location, such as the Eden/Petteril and Caldew/city centre areas in Carlisle. Also of interest are those studies which carried out a systematic examination of flood risk on a river or catchment, such as the flood mapping studies on the Kent and Derwent, and the Catchment Flood Management Plan for the Eden.

Other organisations have reviewed the flooding and its impacts. The Government Office for the North West completed a review titled *'Carlisle storms and associated flooding – a multi-agency debrief report'* in July 2005. Carlisle City Council also undertook extensive reviews.

The report is a reference document for use in the future and the reader needs a basic understanding of meteorology, hydrology and flood risk management. It complements the Environment Agency's own publication *'A review of the floods in northern England and North Wales January 2005'* of July 2005. This contains a large number of recommendations which cover: -

- flood protection
- forecasting
- flood warnings
- incident management

Therefore, this report does not overlap with the above or deal with issues such as the performance of the Environment Agency and lessons learnt.

Other organisations and people kindly provided information to help with the study and their assistance is gratefully acknowledged.

2.3 Structure of the Report

The report is structured in the following way:-

- Section 3 describes the meteorology of 6 to 8 January and the period beforehand. This is a self contained section which is taken directly from the report prepared by the Met Office.
- Section 4 covers the hydrological aspects, including measured rainfall and river flows. It also deals with the performance of the gauging stations and rain gauges during the event.
- Section 5 deals with the flood warnings which were issued.
- Section 6 details the impacts of flooding and the principal flooded areas. It also covers the wider impacts, such as the effects on the transport network and health.
- Section 7 summarises the flood risk management improvements implemented since 2005.
- Section 8 highlights the key conclusions of the study.
- Section 9 acknowledges the people and organisations that assisted in the study.
- Section 10 lists the reference material.

Figure 2-1: Main Rivers and Key Locations affected in Cumbria

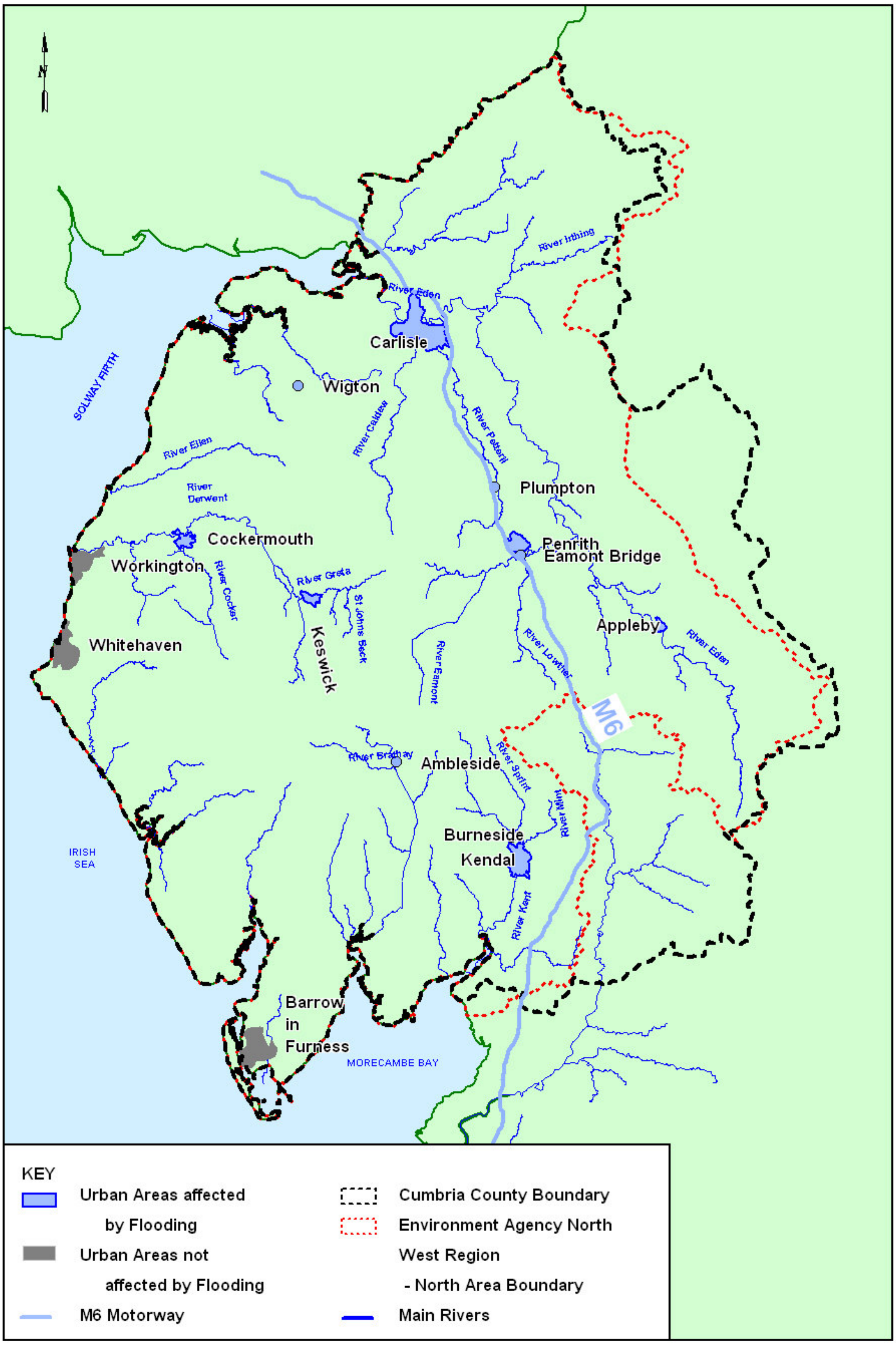
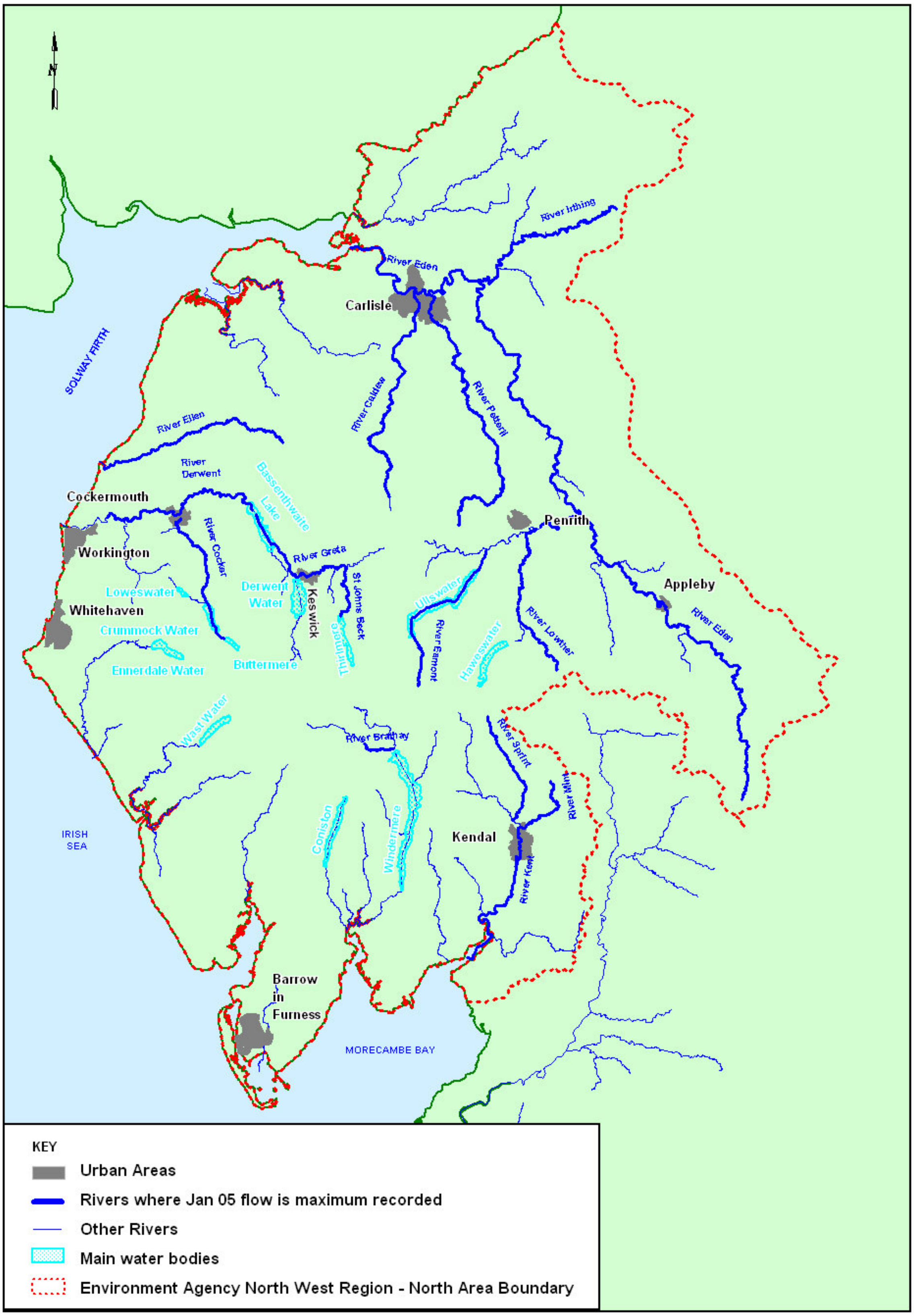


Figure 2-2: Rivers in Cumbria where Maximum Flow was recorded in January 2005



3 METEOROLOGICAL OVERVIEW

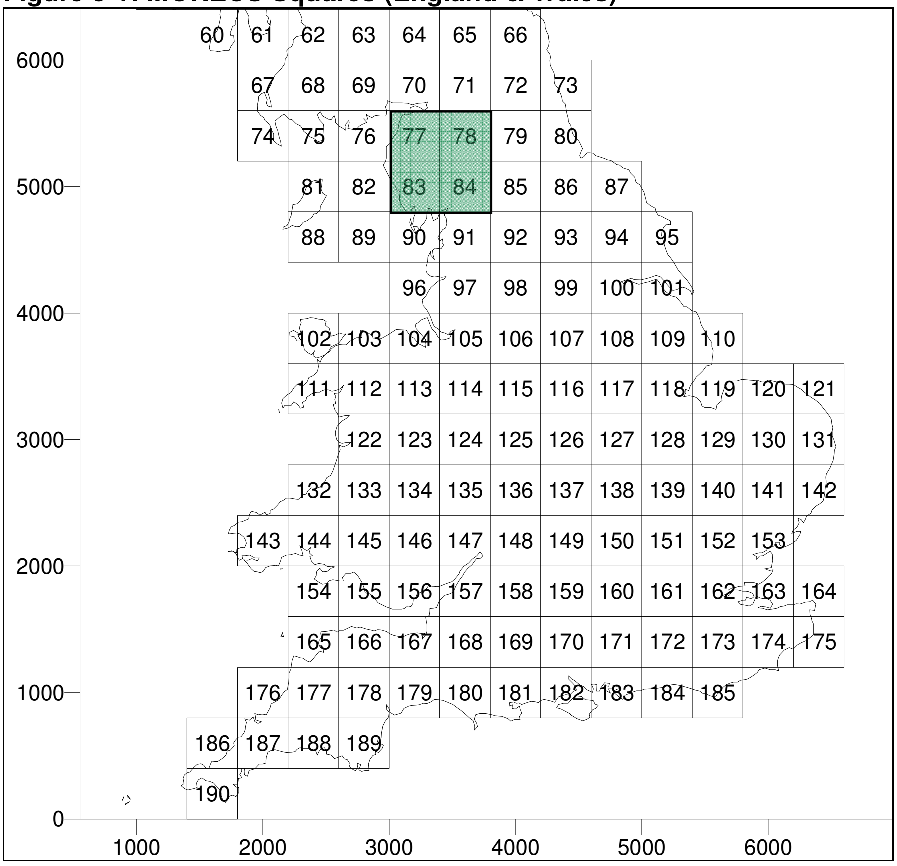
3.1 Introduction

This section is taken directly from the report, “Flooding in Cumbria on 7-8 January 2005 – A Study of meteorological conditions”, which was produced by the Met Office. It discusses the meteorological conditions that generated the heavy rain and the characteristics observed by radar and the gauges. A detailed description of the important aspects of the meteorological situation is provided and compared to previous studies of orographic rainfall. An assessment is made of the weather forecasts issued by the Met Office, both at long and short ranges. The assessment points out the relative strengths and weaknesses of each forecast in relation to the observed conditions. A qualitative assessment is made of the rarity of the underlying meteorological conditions which lead to the extreme rainfall.

3.2 Antecedent conditions

The soil moisture deficit (SMD) was assessed using the Met Office Rainfall & Evaporation Calculation System (MORECS) data for the Cumbria area (squares 77, 78, 83 & 84 shown shaded in Figure 3-1). This was compared with SMD data derived from the Met Office Surface Exchange System (MOSES) data at 5km resolution.

Figure 3-1: MORECS Squares (England & Wales)



3.2.1 Antecedent Soil Moisture Deficit from MORECS

Antecedent conditions were considered in terms of SMD. SMD is the amount of rainfall required to restore soil to its field capacity and an indicator of soil wetness, hence runoff. Values for SMD were obtained from MORECS for the four squares 77, 78, 83 and 84 (shown in Figure 3-1) which include the flood affected areas. Values for grass were considered more representative and selected in preference to the alternative values for bare soil.

Monthly average SMD values are shown for the months of December 2004 and January 2005 in Table 3-1. In general, monthly average values were similar to the long term average (1961-1990) indicating that soil conditions were not unusually wet over the period. SMD values approximately double the long term average (LTA) in the north of the region (square 77) indicating drier than average soil conditions during the period.

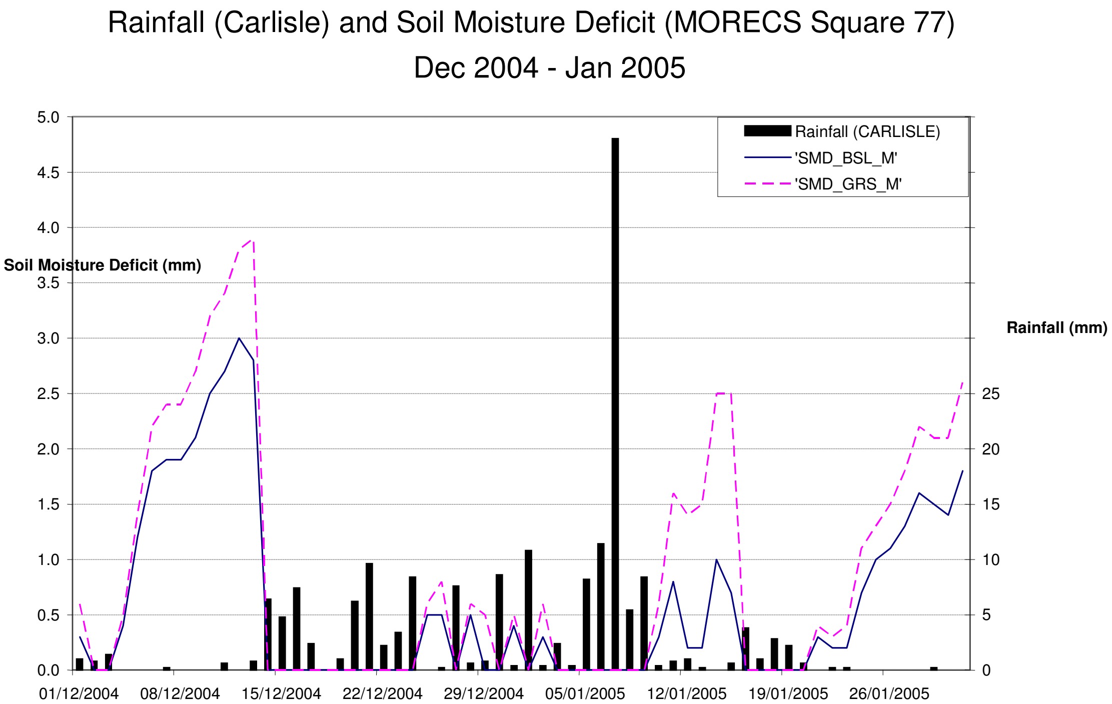
Table 3-1: Monthly SMD for December 2004 and January 2005 from MORECS (mm)

	Square 77		Square 78		Square 83		Square 84	
	SMD for Grass	**LTA* SMD for Grass**	**SMD for Grass**	**LTA* SMD for Grass**	**SMD for Grass**	**LTA* SMD for Grass**	**SMD for Grass**	**LTA* SMD for Grass**
Dec 2004	1.0	0.4	0.3	1.6	0.0	0.3	0.2	0.3
Jan 2005	0.9	0.4	0.6	0.5	0.6	0.2	0.6	0.3

* 1961-1990

Daily SMD values for the week leading up to the event are shown in Table 3-2. Zero SMD values for the 5 days preceding the event indicate soil conditions close to field capacity. Once SMD reaches field capacity, excess rainfall is assumed to produce runoff and infiltration.

Figure 3-2: Rainfall and Soil Moisture



SMD_BSL_M = Median SMD for Bare Soil
SMD_GRS_M = Median SMD for Grass

Table 3-2: Daily SMD (mm) for Grass (SMD_GRS_M) for early January 2005

Date	Square 77	Square 78	Square 83	Square 84
1 January 2005	0.0	0.6	0.0	0.2
2 January 2005	0.6	0.0	0.8	0.0
3 January 2005	0.0	0.0	0.0	0.0
4 January 2005	0.0	0.4	0.0	0.0
5 January 2005	0.0	0.6	0.0	0.4
6 January 2005	0.0	0.6	0.0	0.5
7 January 2005	0.0	0.6	0.0	0.7
8 January 2005	0.0	0.3	1.5	0.7

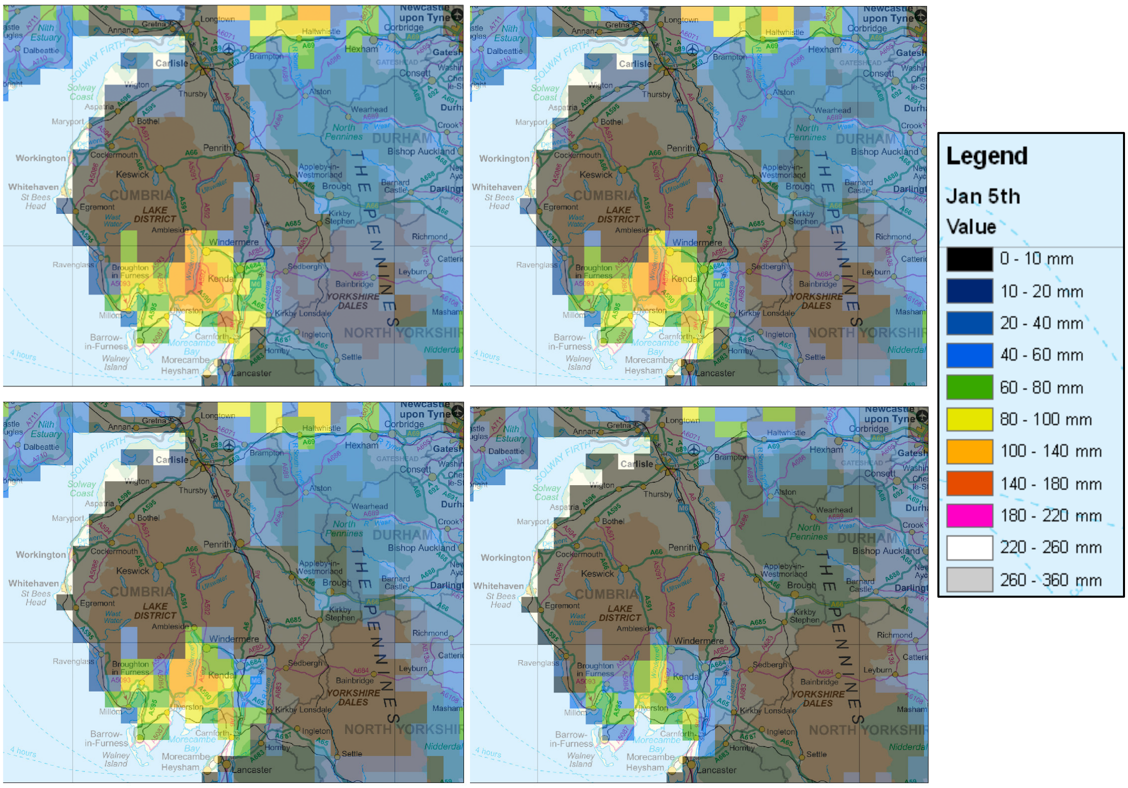
The relationship between rainfall and SMD is shown graphically (for grass and bare soil) for square 77 in Figure 3-1 which shows frequent periods of light rain interspersed with short drier periods in the days leading up to the event.

3.2.2 Antecedent Soil Moisture Deficit from MOSES

MOSES is the Met Office Surface Exchange Scheme which is used to model soil moisture, runoff and other hydrological variables at approximately 5km resolution. The method differs from MORECS in that SMD is not calculated explicitly. Rather, it is derived from modelled soil moisture hence it is not directly comparable with MORECS SMD. However, it provides additional information to add confidence to the analysis.

Values of SMD from MOSES were compared for the days leading up to and during the event. SMD values at 0900 on 5-8 January are shown in Figure 3-3 and indicate generally low (0-10mm) SMDs in the region, with higher values in southern areas.

Figure 3-3: Soil Moisture Deficit from MOSES at 5km resolution



3.3 Meteorological analysis

The meteorological analysis was carried out using analysed charts produced in the Ops Centre at Exeter and other data, including satellite imagery. More detailed structures have been examined using the Met Office Mesoscale Model outputs as a diagnostic tool.

3.3.1 Synoptic overview

Surface synoptic charts for the period from 1200 co-ordinated universal time (UTC) on Thursday 6 January to 0600 UTC on 8 January at six hourly intervals are shown in Figure 3-4.

These charts are produced at the Ops Centre in Exeter and are based on an analysis using data assimilation in the Met Office global model. The model analysis is modified by senior forecasters according to additional evidence from satellite imagery and other data. At 1200 UTC on 6 January an eastward extension of the Azores high had become established across southern and central parts of mainland Europe. A deep area of low pressure was present in the Iceland area with an associated warm front moving away east after crossing the British Isles. This warm front introduced a very mild and moist tropical maritime airmass into the UK on strong to gale force south-westerly winds. The tropical airmass originated from very low latitudes southwest of the Azores. A ship with call sign "PGDO" at 33N 34W was reporting a dew point temperature of 17°C and sea temperature of 18°C. This region provided a continuing source of very warm and moist air which moved north-eastwards in the low-level flow (indicated by a black arrow in Figure 3-4.). Separating the warm tropical maritime airmass from a much colder polar airmass was a cold front. At 1200 UTC on 6 January this front lay from 61N 10W for circa 5000km down to the Caribbean. Up to 0600 UTC on Friday 7 January this front was analysed as having a double structure as it made slow and erratic south-eastward progress into Northern Ireland and Scotland. The easternmost front marked the western boundary of the warmest tropical air and the western front the transition to polar air at the surface. At 1200 UTC on 6 January a third cold front lying from 51N 34W to 41N 55W indicated the leading edge of a very cold polar airmass. By 0000 UTC on 7 January this front had caught up with the other two and later, the injection of very cold air from this front caused the rapid development of a very deep and vigorous low pressure system that crossed Scotland during the morning of Saturday 8 January.

Throughout most of the day on Friday 7 January the main cold front was quasi-stationary over Northern Ireland and northern England. Minor waves or ripples propagated quickly north-eastwards along the front meaning that, at times, the front moved south into Cumbria and then retreated northwards again. So, for most of Friday the front was close to the Cumbrian fells which stayed in the warm and moist tropical airmass all day. However, by 1200 UTC a new low pressure system was starting to form on the western-most front at circa 50N 22W. This development can be seen in the satellite imagery in Figure 3-5 for 1210 UTC as a "cloud leaf". By 0000 UTC on 8 January the low was just off western Ireland with a pressure of 980hPa with a more definite signature now evident in the satellite imagery at 2159 UTC. The effect of this development was to quickly strengthen the south-westerly airflow in the Irish Sea on Friday evening. Just after midnight on Saturday 8 January the low deepened rapidly and by 0600 UTC had a pressure of 969hPa over the Borders. The deepening meant that the cold front pushed quickly eastwards through Cumbria on a severe gale force westerly wind. As the low deepened rapidly an occluded frontal system developed very quickly and wrapped itself around the depression bringing heavy rain back south into Cumbria accompanied by a storm force westerly wind of circa 60 knots for a time early on Saturday morning. The cloud from this occlusion coming round the low in the shape of a hook can be seen in the 0536 UTC satellite image in Figure 3-5. During Saturday the deep low moved away into the North Sea and winds quickly died down as cold air spread south introducing wintry showers into northern England.

Figure 3-4: Maps showing Met Office analysed mean sea level isobars and fronts from 1200 UTC 6 January 2005 to 0600 UTC 8 January 2005 at six hourly intervals. Bold arrow indicates source of warm and moist air moving north-eastwards at 1200 UTC on 6 January.

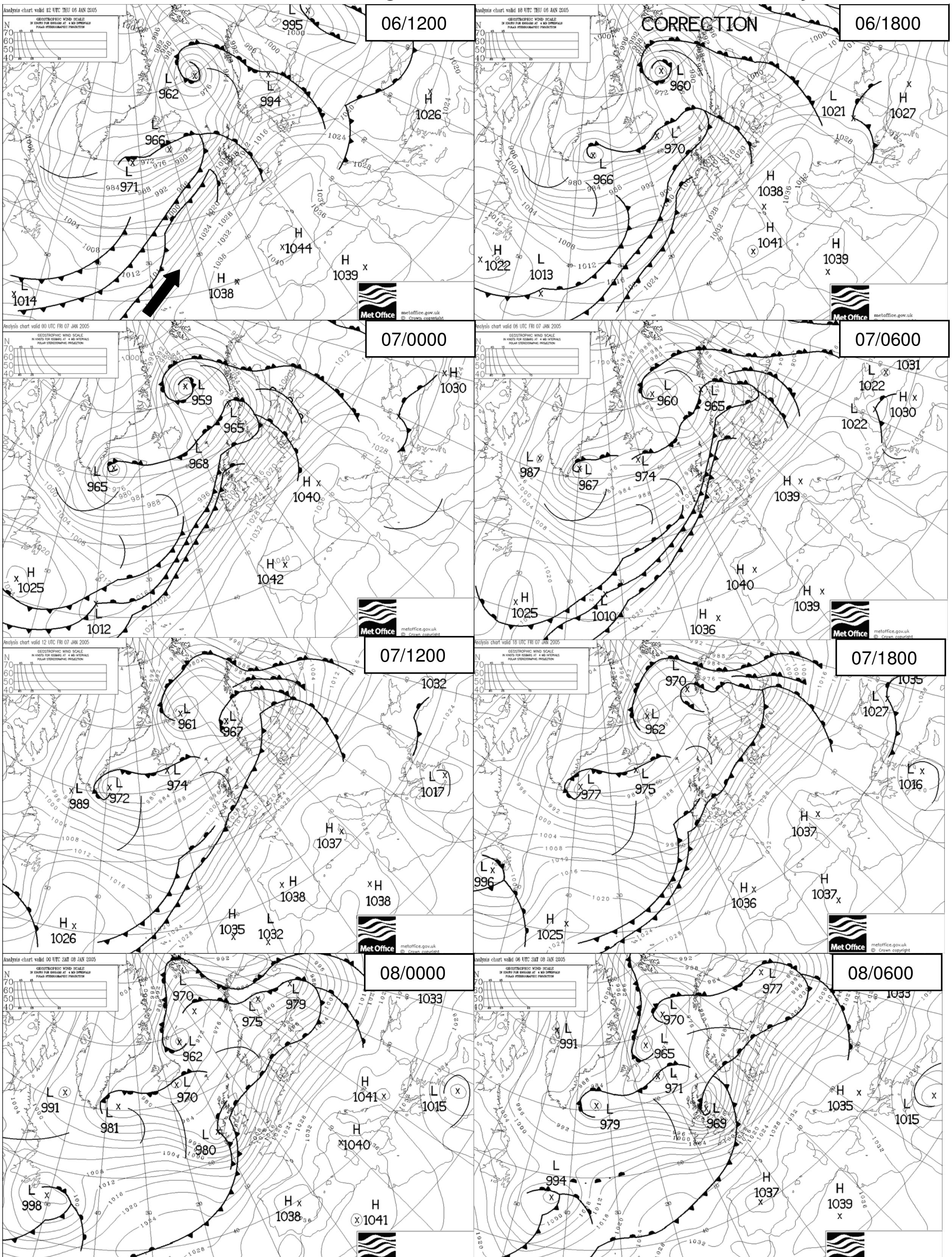
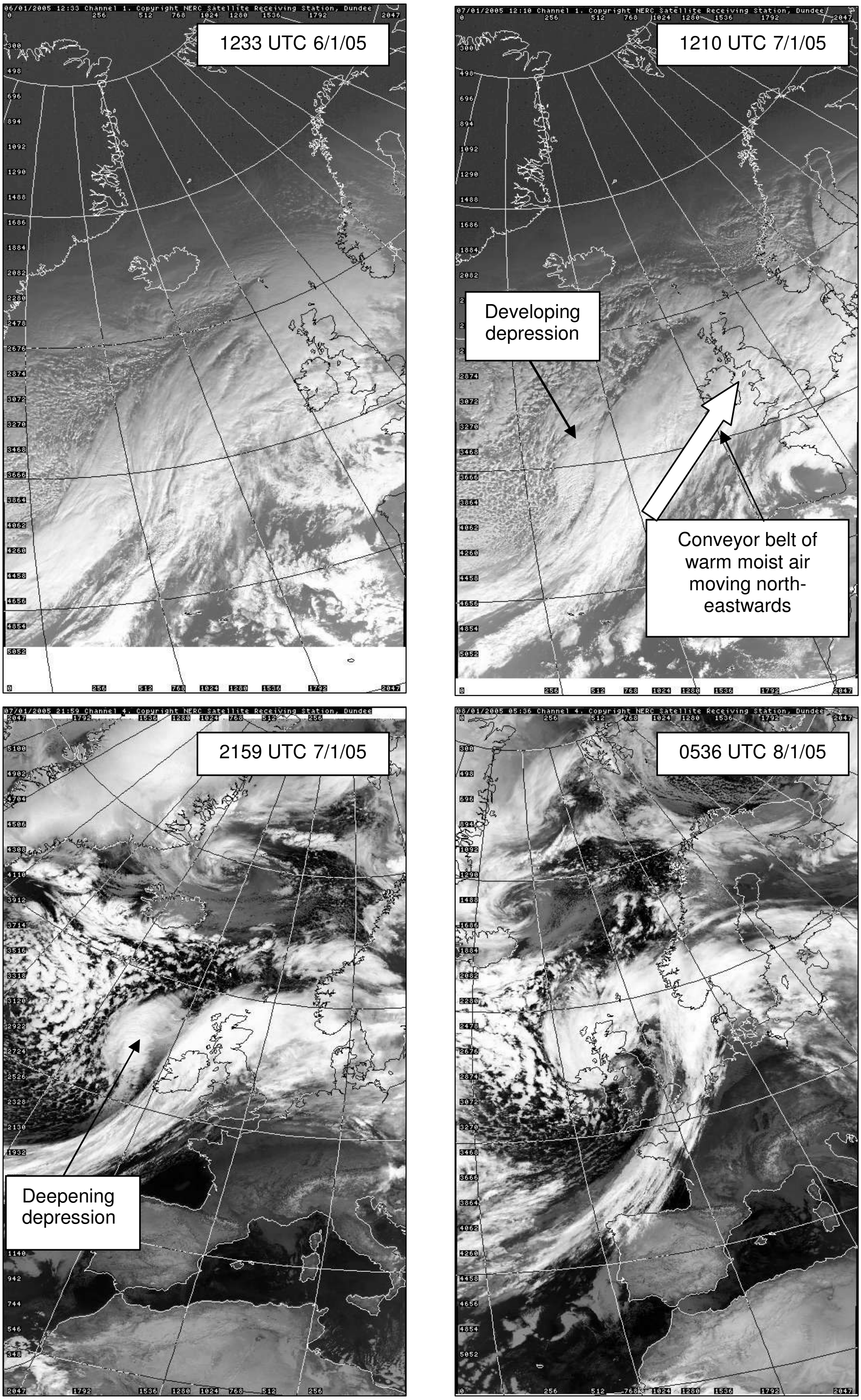


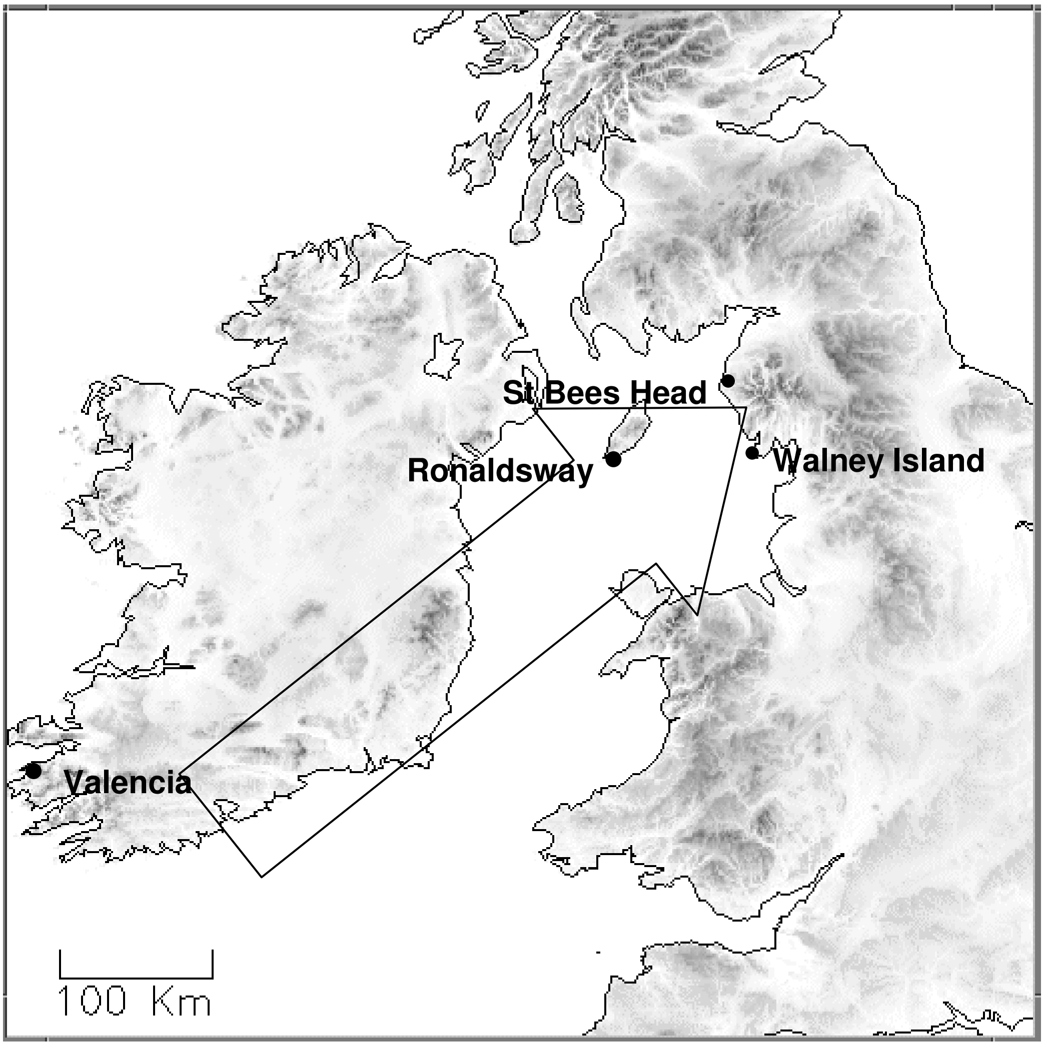
Figure 3-5: Satellite pictures from the University of Dundee on 6, 7 and 8 January 2005 from the Advanced Very High Resolution Radiometer (AVHRR) polar orbiting satellite. The locations of a developing and then deepening depression are indicated. The position of the "conveyor belt" of warm moist air is also shown.



3.3.2 Detailed analysis

A map showing a schematic of the warm and moist low-level airflow (large arrow) and some key places mentioned later in the text is shown in Figure 3-6.

Figure 3-6: Map showing relief of part of British Isles, the direction of flow of moist low-level air and the location of places mentioned in the text.



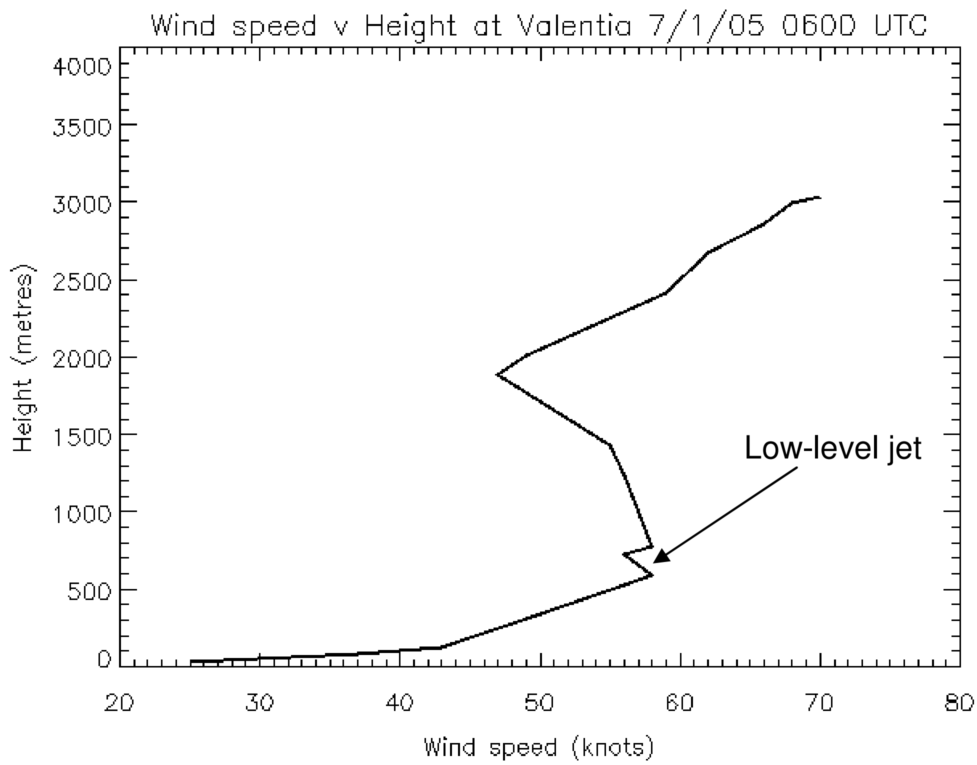
Valentia observatory in SW Ireland was one of the first places in Britain to pick up the warm and moist south-westerly air stream and so data from there have been used to track temporal changes during the period from 1200 UTC 6 January to 1200 UTC 8 January. Valentia observatory samples the atmosphere using radiosondes four times per day and a subset of the data is shown in Table 3-3. Relative humidity indicates how close the air was to saturation. Total precipitable water content (in mm) is equivalent to the amount of liquid precipitation that would result if all the water vapour in a column of air instantaneously condensed. It is therefore a direct and rather convenient measure of moisture content aloft. The wet-bulb potential temperature at a pressure level of 850hPa, which is approximately 1500m above sea level (asl), is used as a convenient airmass tracer. High values (coloured red in Table 3-3) show tropical air and low values (blue in Table 3-3) indicate polar air.

Table 3-3:Table showing information from Valentia radiosonde soundings taken at six hourly intervals from 1200 UTC 6 January 2005 to 1200 UTC 8 January 2005

Valentia observatory (51.93°N 10.25°W)					
Date/time (UTC)	**Temp (ºC) at 925hPa (approx 850m asl)**	**Relative humidity at 925hPa (approx 850m asl)**	**Wind speed and direction (deg/knots) at 925hPa**	**Total precipitable water content (mm) at 850hPa**	**Wet-bulb potential temp at 850hPa**
6 Jan 05, 1200	5.4	94	225/47	18.1	10
6 Jan 05, 1800	6.8	96	220/45	23.5	11
7 Jan 05, 0000	7.6	87	230/60	26.2	11
7 Jan 05, 0600	9.4	95	235/56	25.8	12
7 Jan 05, 1200	9.2	90	235/54	25.5	11
7 Jan 05, 1800	8.2	95	220/72	25.9	10
8 Jan 05, 0000	6.2	93	225/51	17.1	7
8 Jan 05, 0600	0.4	72	270/49	9.2	1
8 Jan 05, 1200	0.0	82	270/39	7.9	0

Table 3-3 clearly shows the transition from a tropical airmass with wet-bulb potential temperatures greater than 10°C up to 1800 UTC 7 January falling to near 0 °C by 0600 UTC 8 January. This change was brought about by the passage of the two cold fronts shown in Figure 3-4 which also caused a veer in the wind direction and a marked drop in temperature. The total precipitable water column shows an increase in water vapour in the tropical airmass from 1200 UTC 6 January to 0000 UTC 7 January. This also coincided with an increase in wind speed to 60 knots at midnight. The air temperature at 925hPa level also rose and the air at that level remained close to saturation with relative humidities over 85%. To examine the wind more closely a vertical profile of wind speed against height was plotted for 0600 UTC 7 January which coincided with the highest temperature at 925hPa and the highest wet-bulb potential temperature at 850hPa. The profile is shown in Figure 3-7.

Figure 3-7: Plot of wind speed according to height above ground at Valencia observatory on 7 January 2005 at 0600 UTC.



This profile is very interesting since it shows a rapid increase in wind speed from near the ground to 600m and then a gradual decrease to 2000m and then an increase again above that level. The peak of the wind speed around 600m is a low-level jet stream and is tied in with the conveyor belt of warm and moist air moving north-eastwards shown in Figure 3-5.

Clearly Valentia observatory was only able to sample air over the station. In order to get a fuller picture of the wind field, analyses from the Met Office Mesoscale Model were used. These are produced using model forecasts as a first-guess and then assimilating all available data such as radiosondes. Maps of wind speed and direction analyses at 12 hourly intervals from 1800 UTC 6 January to 0600 UTC on 8 January at a model level 610m above ground are shown in Figure 3-8.

The map for 1800 UTC on the 6 January shows a pulse of winds greater than 50 knots over the Irish Sea. By 0000 UTC 7 January (not shown) these had increased and the affected area had expanded. The map for 0600 UTC 7 January shows the analysed 56 knots at Valentia and a core of very strong south-westerly winds greater than 60 knots extending north-eastwards towards Cumbria. This increase in wind strength was due to the proximity of the cold front combined with the reluctance of the anticyclone over the continent to give way increasing the sea-level pressure gradient. By 1800 UTC the depression forming to the west of Ireland was deepening quickly and this increased the pressure gradient further to bring wind speeds greater than 65 knots into the sea area south of Ireland.

At 0000 UTC 8 January (Figure 3-9) the rapidly deepening depression with light winds north of the centre caused a rapid increase in 610m winds to 75-80 knots over the Irish Sea with 70 knots over Cumbria. By 0600 UTC the winds had veered westerly and strengthened even more over northern Cumbria to 85 knots just south of the occlusion shown in wrapping around the low in Figure 3-4.

The maps showing wind speed and direction become more interesting when they are compared with analyses of relative humidity from the model. These are shown in Figure 3-10. *A level of 1600m above sea-level was chosen as it was this level that was observed to undergo the most temporal change at Valentia observatory (data not shown).* The level plotted is relative to sea-level which means that it is only 700m above the highest Cumbrian fells. At 1800 UTC on 6 January there was an area of high (>90%) relative humidity over the northern part of Irish Sea extending into parts of Northern Ireland. This seemed to be associated with the weak warm front analysed approaching western Ireland at 1200 UTC. Note that the air upwind of Cumbria in the Celtic Sea was relatively dry. By 0000 UTC 7 January this air had become more moist and patches of humid air were evident over Cumbria and over the western up-slopes of the mountains of Wales. However, by 0600 UTC 7 January the whole of the area covered by the strengthening south-westerly winds was close to saturation. The region stayed under the very humid air until 0000 UTC 8 January.

Figure 3-8: Analysis of wind speed and direction at 610m above ground level from the Met Office Mesoscale Model at 12 hourly intervals from 1800 UTC 6 January 2005 to 0600 UTC 8 January 2005 -See key adjacent Figure 3.2.4.

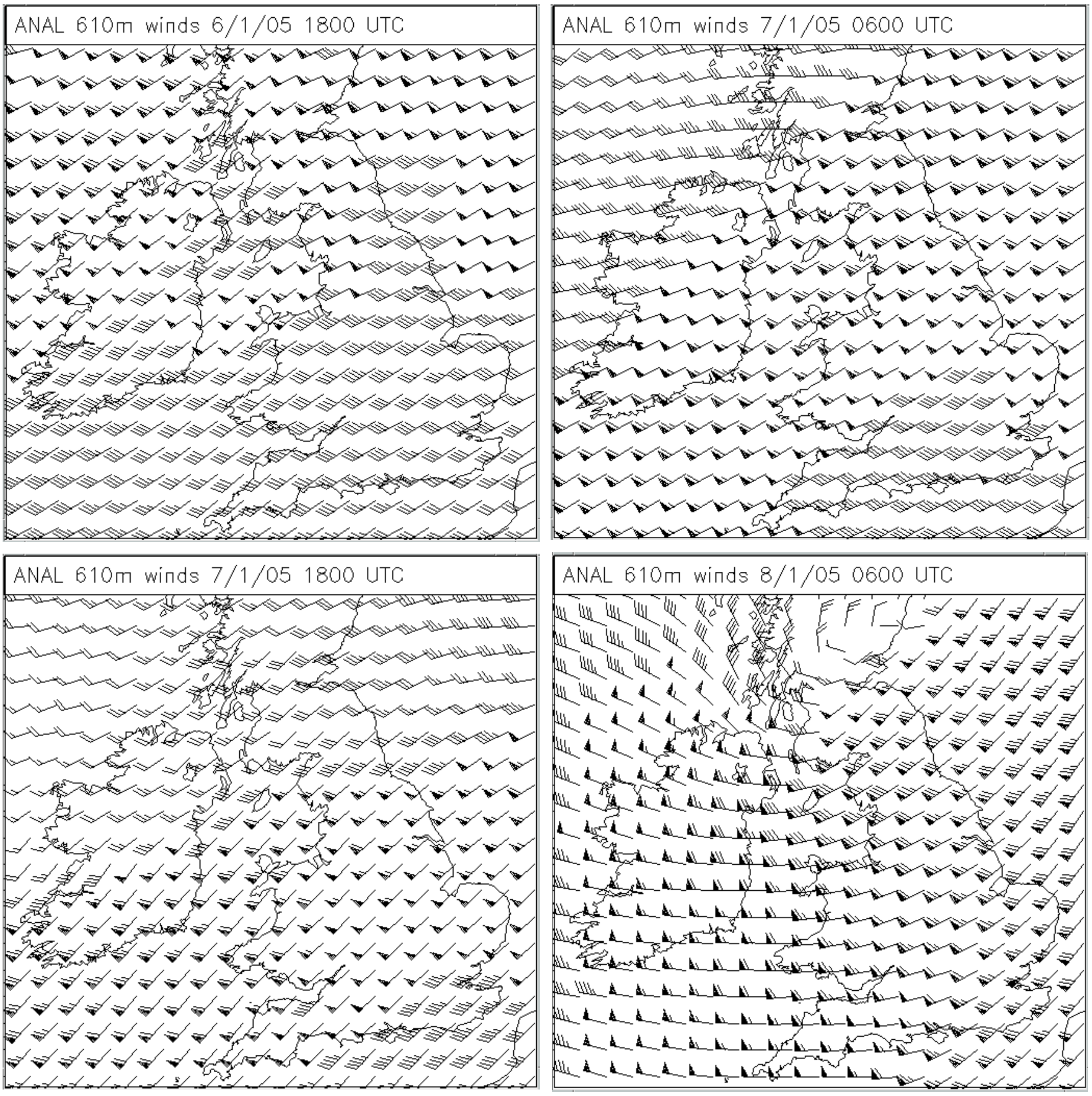


Figure 3-9: Analysis of wind speed and direction at 610m above ground level from the Met Office Mesoscale Model at 0000 UTC 8 January 2005.

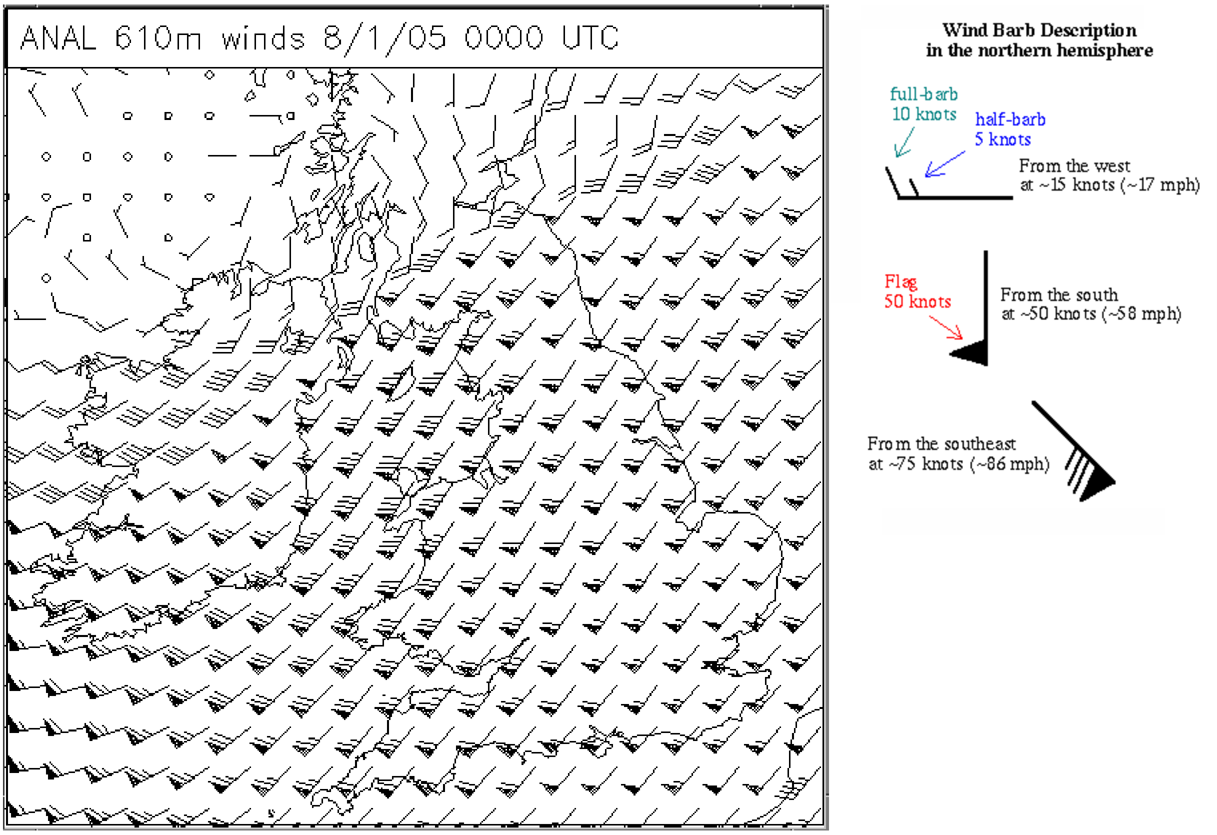
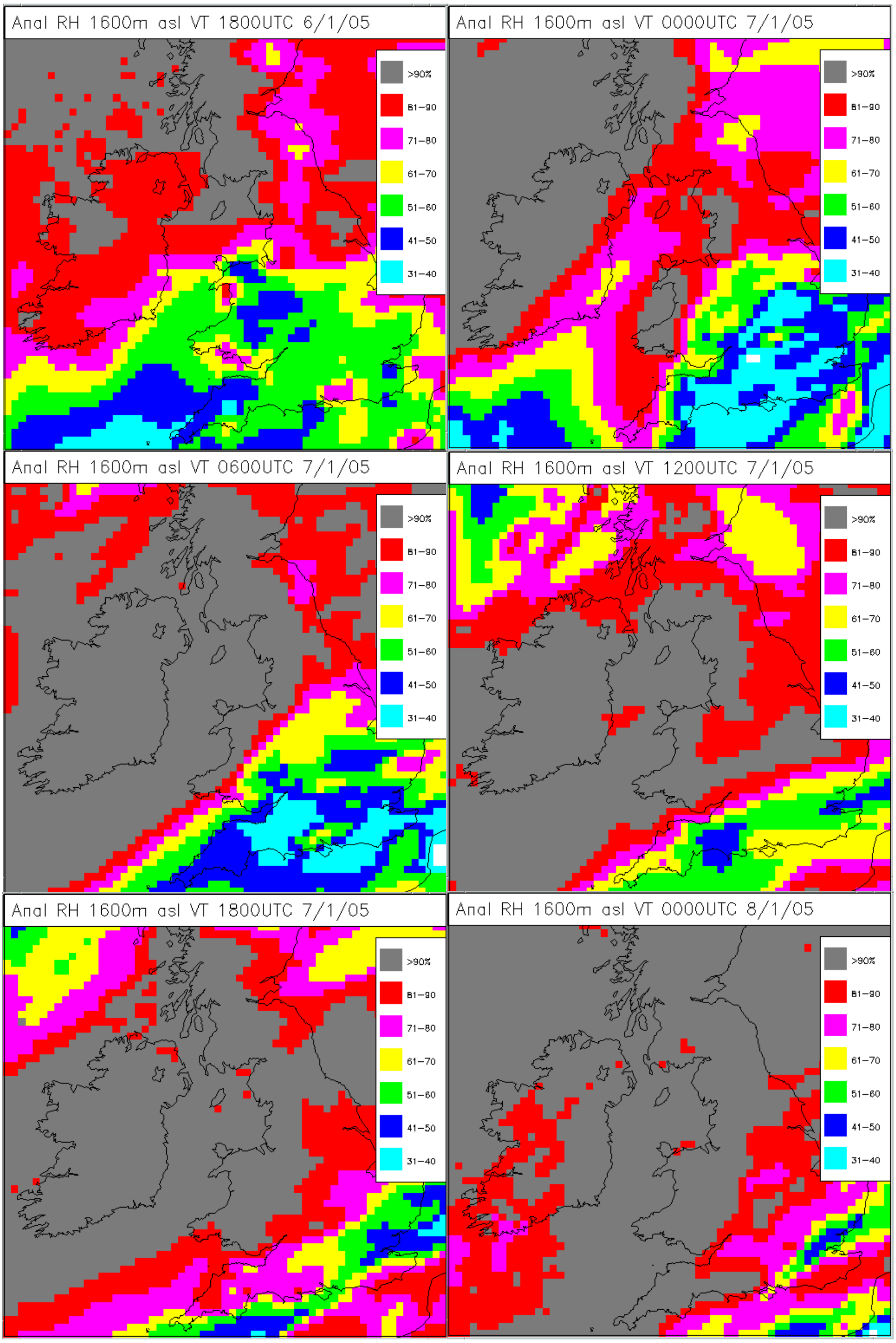
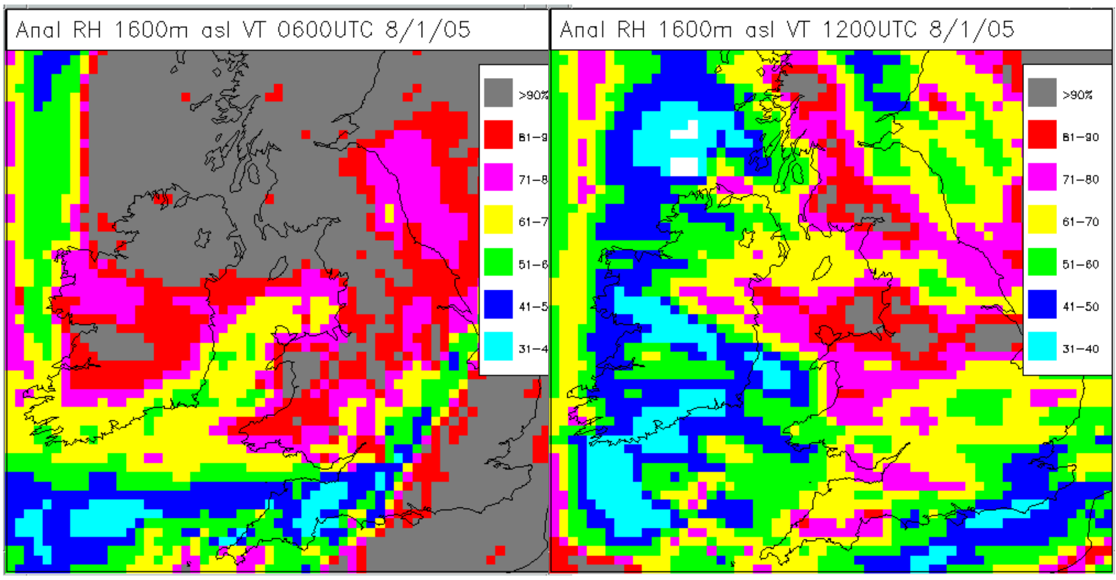


Figure 3-10: Analysis of relative humidity at 1600m asl from the Met Office Mesoscale Model at 6 hourly intervals from 1800 UTC 6 January 2005 to 1200 UTC 8 January 2005.

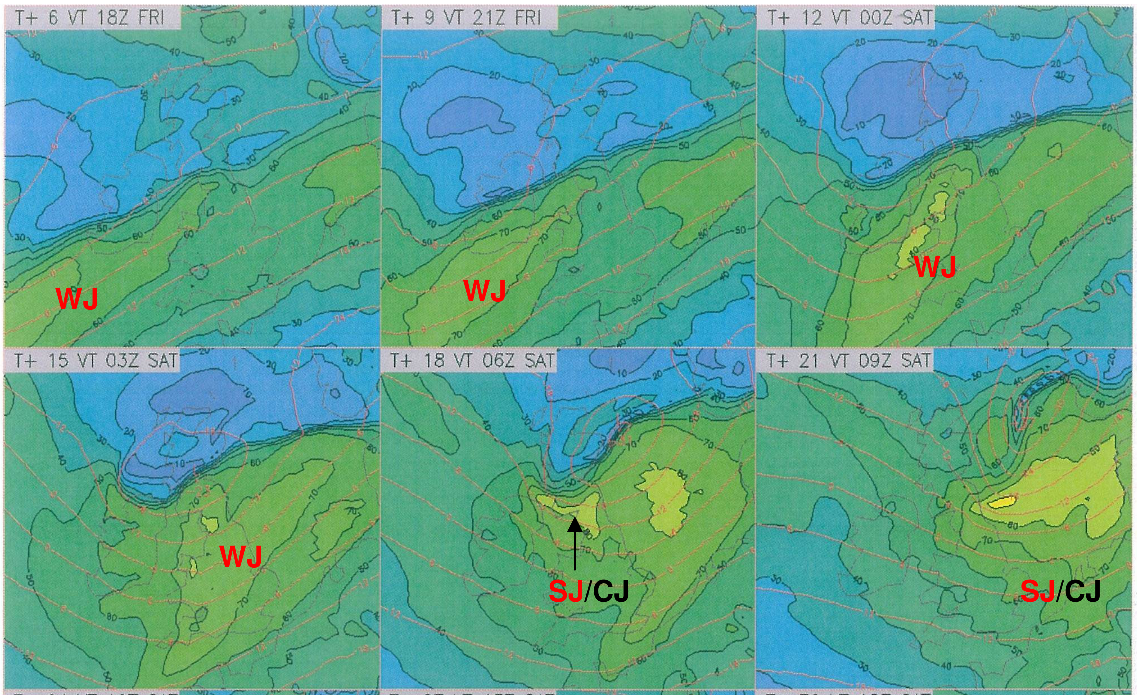




By 0600 UTC on 8 January drier air was coming into the southern Irish Sea but the north remained almost fully saturated near the occlusion. However, by 1200 UTC the north was starting to become drier in the showery westerly polar airmass.

There is convincing evidence of a ‘sting jet’ (SJ) formed on the morning of Saturday 8 January when wind gusted to more than 100mph (>85 knots) across some parts of northern England, with speeds of almost 130mph (>110 knots) on the Pennine peaks. There was an associated dramatic fall in the barometric pressure in as few as six hours, and unusually high wind gusts in the warm conveyor belt jet, increasing from >50 knots to >80 knots over three hours (Figure 3-11, Figure 3-12 and Figure 3-13 provided by Martin Young).

Figure 3-11: Severe gales in the mesoscale model – level-6 winds



SJ = Sting Jet, WJ = Warm Conveyor Belt Jet, CJ = Cold Conveyor Belt Jet

Figure 3-12: Formation of a Sting Jet: 03Z 8 January 2005.

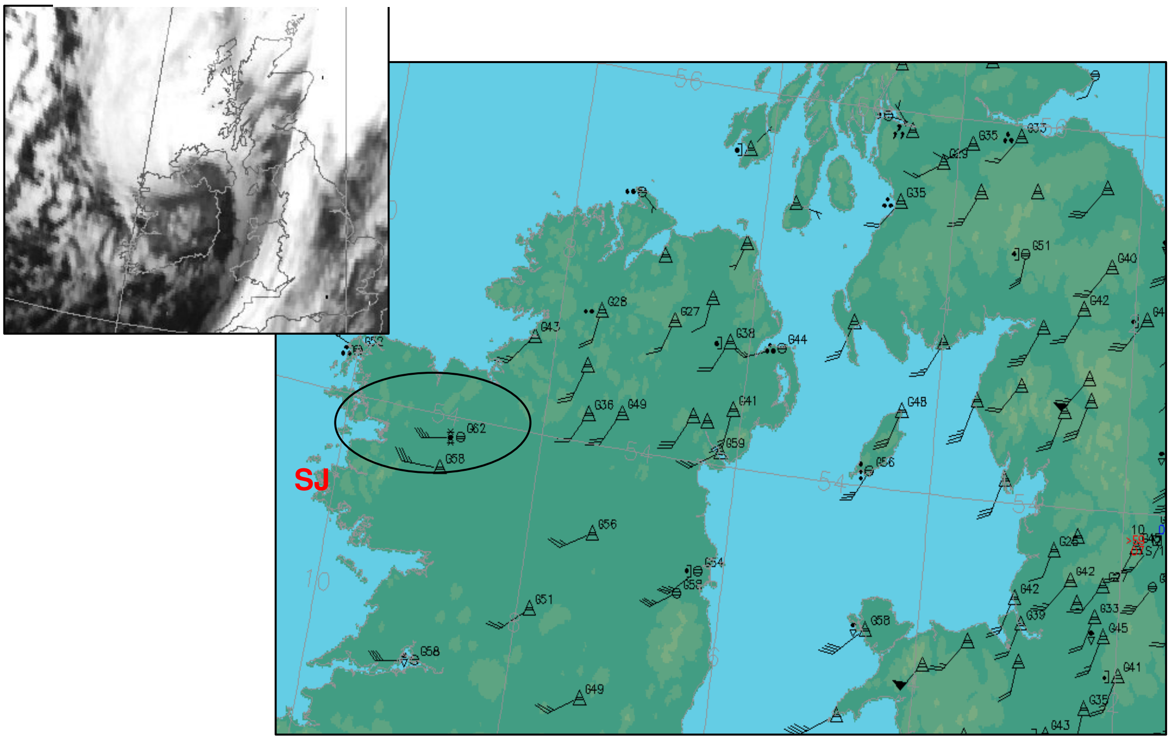
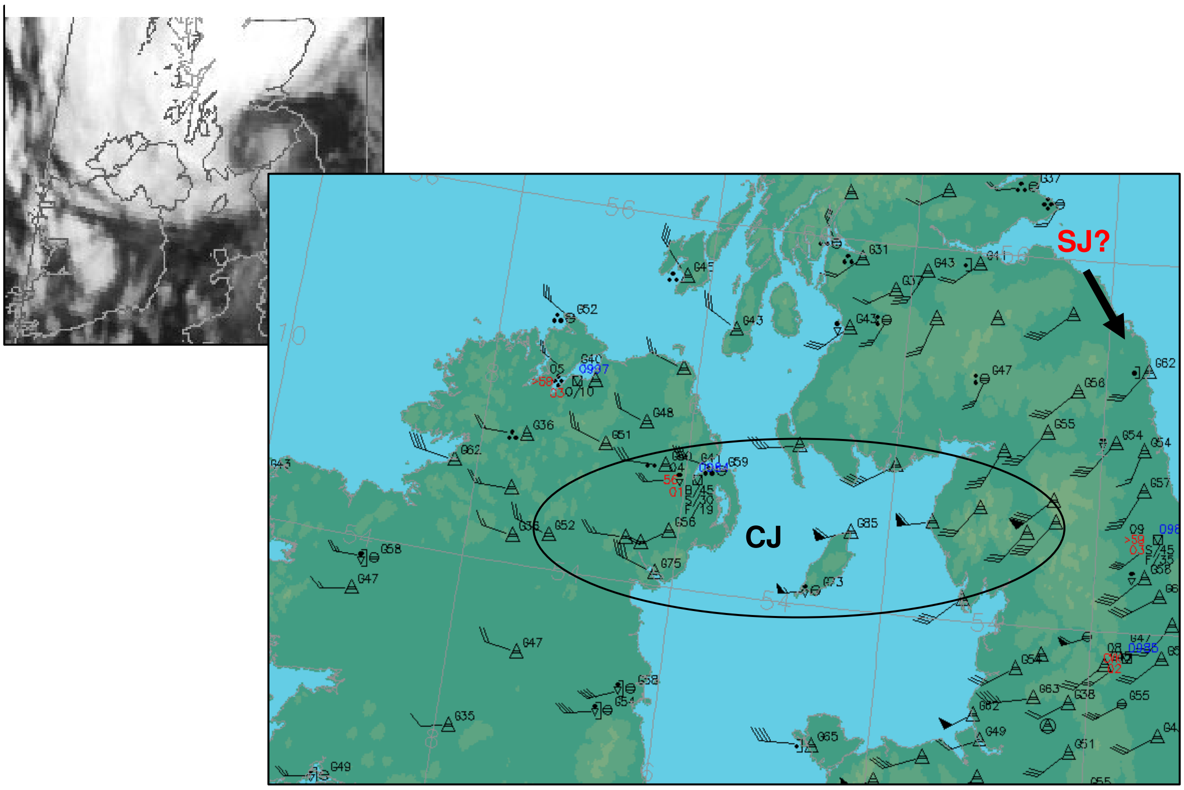


Figure 3-13: Formation of a Sting Jet: 06Z 8 January 2005.



A sting jet is a mesoscale air flow which originates in the cloud head of a rapidly deepening cyclone and gathers speed as it descends towards the tip of the cloud head when it begins to hook around the cyclone centre (See Figure 3-12 and Figure 3-13). It originates at an altitude of 5km (3 miles), within layers of ascending moist air, and is distinct from the usual strong-wind region associated with the warm conveyor belt and main cold front. As the jet descends, it passes through ice crystals that cool it, increase its density and cause it to accelerate to more than 100mph at ground level. There are indications that conditional symmetric instability and evaporation both play a role in its formation but the importance of these processes remains to be quantified. Research into sting jets is ongoing (Clark et al, 2005).

3.3.3 Discussion

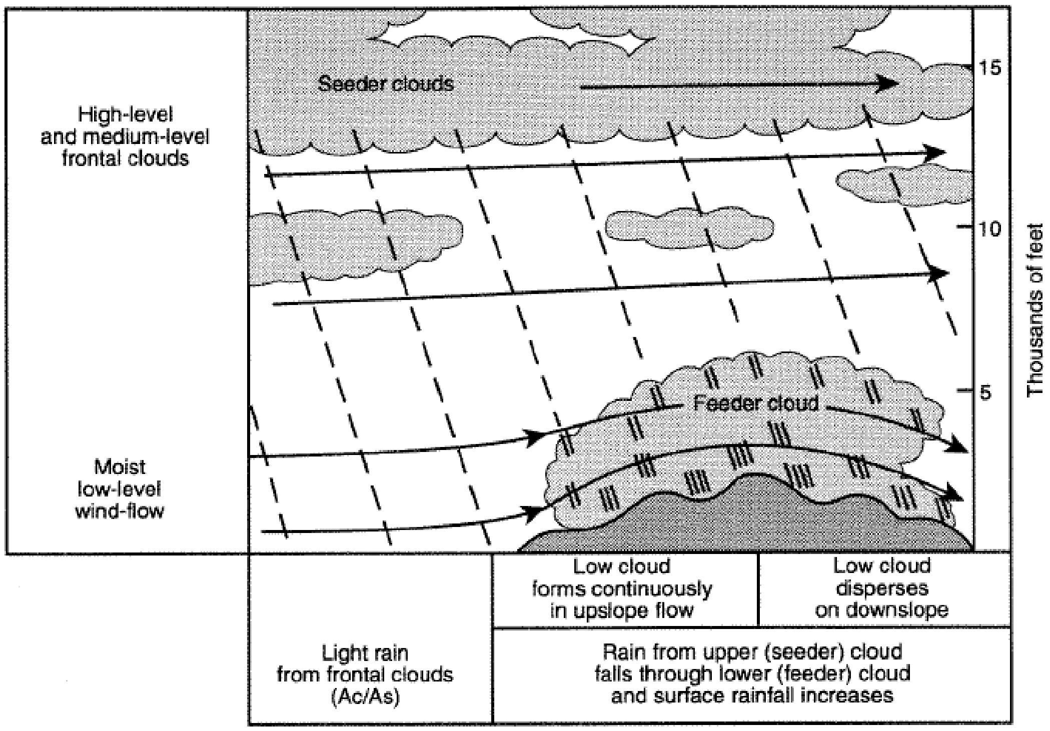
Clearly there appeared to be four important atmospheric processes contributing to the extreme rainfall event and its cessation.

- The very moist tropical south-westerly airflow rising over the Cumbrian fells giving orographic rain.
- Rainfall from the weak warm and, more importantly, strong cold frontal systems.
- Rainfall from the occlusion wrapped around the rapidly developing low and the introduction of a much colder and drier but showery polar airmass.
- Evidence suggests the presence of a ‘sting jet’, a descending stream of air accelerating to more than 100mph (>85 knots) at ground level.

Generally orographic rainfall occurs when a very moist low-level air flow is forced to rise over high ground forming thick low cloud (stratus) layers. These clouds by themselves may not produce a lot of precipitation. However, if rain is already falling from upper cloud layers (seeder clouds) above the low stratus layers, it will fall through the low-level (feeder) cloud, capturing the droplets within and considerably enhancing the rainfall rate at the surface. This process is illustrated in Figure 3-14.
The degree of precipitation enhancement depends on:

- Seeder (rainfall) rate > 0.5mm/h
- High wet-bulb potential temperature at 850hPa
- Near saturated air upwind
- Strong low-level wind ahead of cold front (>60 knots for heaviest rain)
- Favourable topography (not too steep)

Figure 3-14: Schematic showing the seeder/feeder process required for heavy orographic rainfall. (Reproduced from the Met Office Forecaster’s Reference book)



Looking first at the formation of low cloud over the Cumbrian fells it is useful to examine a time sequence of cloud observations from the three surface observing stations shown in Figure 3-6 (Ronaldsway, St Bees Head and Walney Island). These are shown in Table 3-4.

Table 3-4: Sequence of cloud observations at three hourly intervals from 1200 UTC 6 January 2005 to 0600 UTC 8 January 2005 from observing stations at Ronaldsway, Walney Island and St Bees Head.

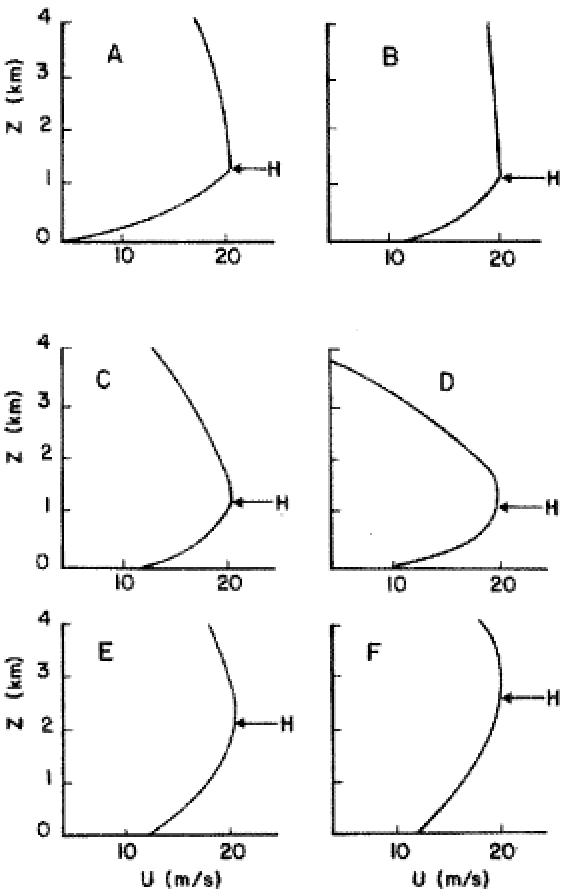
Reported cloud base layers (amounts in oktas / heights in ft above ground)			
Date/time (UTC)	**Ronaldsway 54.08°N 4.63°W 70 feet asl**	**Walney Island 54.12°N 3.25°W 45 feet asl**	**St Bees Head 54.52°N 3.60°W 410 feet asl**
6 Jan 2005, 1200	8/2200 1/1200	7/5000 4/3800 1/2000	8/2000
6 Jan 2005, 1500	7/3000 1/1000	7/3500 1/900	7/400
6 Jan 2005, 1800	8/3200 4/1200	7/1000	7/1100 4/300
6 Jan 2005, 2100	8/2400 3/1200	3/2300 7/1300	7/2700 6/1500
7 Jan 2005, 0000	8/3000 6/1000	8/900	8/400
7 Jan 2005, 0300	8/2500 2/700	8/1800	8/300
7 Jan 2005, 0600	8/2600 3/700	8/900	N/A
7 Jan 2005, 0900	8/2200 1/500	8/700	N/A
7 Jan 2005, 1200	8/2000 6/700 3/200	8/700	7/<100
7 Jan 2005, 1500	8/400 6/200	8/600	8/<100
7 Jan 2005, 1800	8/5000 6/2500 3/600	7/500	8/<100
7 Jan 2005, 2100	8/1300 5/900	N/A	8/<100
8 Jan 2005, 0000	8/1300	4/2800 6/1500	8/300
8 Jan 2005, 0300	8/5000 6/2000 4/1000	7/2700 6/1000	8/700
8 Jan 2005, 0600	7/3300 5/2000	4/4800 4/3900 5/2300	N/A
All low cloud layers are shown as amount/base with the amount in oktas of sky covered and the height of the cloud base in feet			

At Ronaldsway airport on the Isle of Man low cloud sheets with bases below 1000 feet were generally broken but with full cover at 400 feet asl at 1500 UTC 7 January. However, at Walney Island, as near saturated air began to rise to go over the hills inland, extensive low cloud with the base lowering to 500 feet was observed on 7 January. At St Bees Head, 365 feet higher than Walney Island cloud bases descended to less than 100 feet above ground and did not clear until during the morning of 8 January when the drier polar air arrived. Further south at Walney Island the low cloud cleared slightly faster. Clearly these observations show that just upwind of the Cumbrian fells low cloud formed readily in the moist south-westerly air flow. These became the feeder clouds in the model depicted in Figure 3-14.

The Valentia data (Table 3-3) shows that the south-westerly air mass had a high value (for early January) of wet-bulb potential temperature at 850hPa until 0000 UTC 8 January. The Valentia data and the Mesoscale Model relative humidity analyses showed near saturated conditions upwind of Cumbria which were driven directly onto the Cumbrian fells by a strong and strengthening south-westerly low-level wind over 60 knots. Radar data (discussed in Section 3.3.4) and observations indicated frontal rainfall rates over 0.5mm/h falling from thick cloud layers as evidenced by the satellite pictures in Figure 3-5. Therefore, there is strong evidence for all the conditions required for very heavy rainfall from a feeder/seeder mechanism over the Cumbrian fells.

In a paper by Robichaud and Austin (1988) a modelling study showed that rainfall falling from a feeder/seeder mechanism could be considerably increased given optimum variation in the vertical of wind strength. The vertical wind profiles from the paper are reproduced in Figure 3-15.

Figure 3-15: Diagram reproduced from Robichaud and Austin (1988) showing variation of wind speed with height for six scenarios used in a modelling study of orographic rain produced by a feeder/seeder mechanism.



Robichaud and Austin discovered that if a low-level jet has a strong curvature below the jet maximum at height H and a relatively much weaker curvature above as, for example, in cases A and B, then vertical velocities are increased leading to heavier rainfall than in environments with other wind profiles. This is interesting since the vertical wind profile in Figure 3-7 is similar to profile A in the vicinity of the low-level maximum allowing for scale adjustments. The vertical wind profile could, therefore, be another important factor in precipitation enhancement over Cumbria.

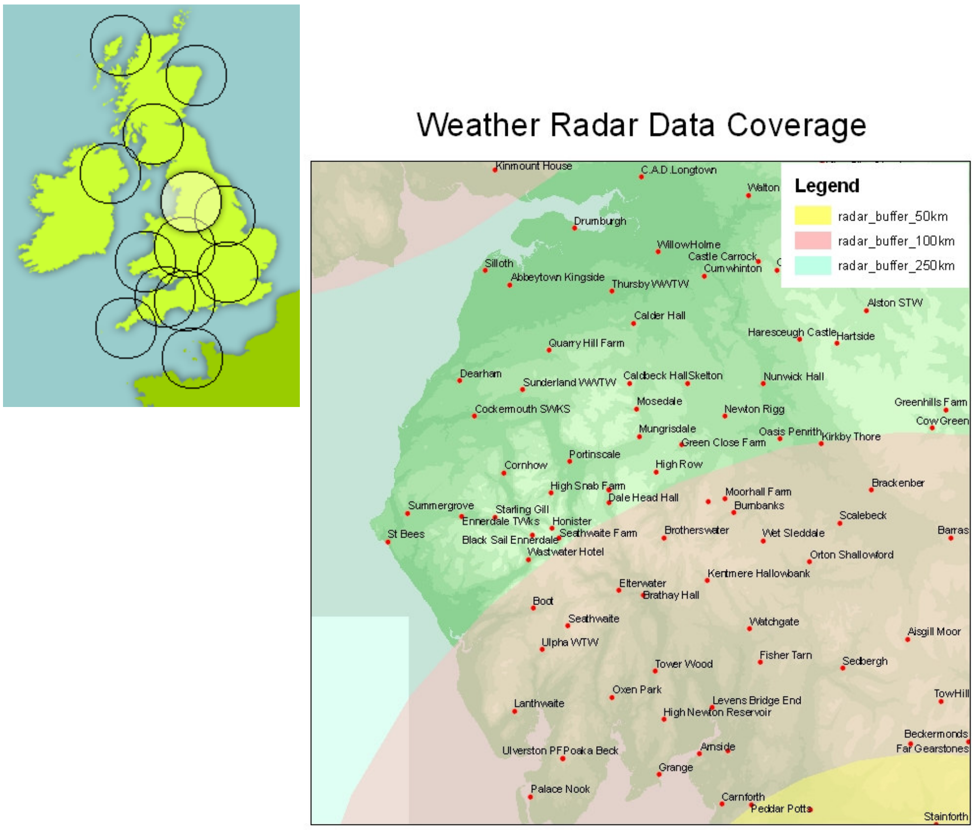
3.3.4 Radar data

A map showing UK radars and the edge of 2km resolution coverage from each radar is shown in Figure 3-16. Note that only the southern part of Cumbria has data at 2km resolution. This means that heavy rain shown in the northern half of Cumbria at 5km resolution is likely to be more intense at smaller space scales. Also, precipitation at low altitudes is likely to be more intense than detected by the radar, as this will be below the scanning beam. The rainfall was strongly influenced by orographic effects, and the radar data has been significantly corrected to account for this. There are other issues associated with Hameldon Hill radar including potential under-estimation of rainfall where there are blockages in the north east of the region, an area which includes the upper Eden catchment. Further discussion of weather radar quality control and correction is available from Harrison et al (2000).

A selection of images from 1200 UTC 6 January to 0600 UTC 8 January at three hourly intervals is shown in Figure 3-17. The images are taken from a composite of all radars in the British Isles with data shown at varying resolution. Data are at 1km resolution close to radar sites, decreasing to 2km and then 5km as distance from a site increases.

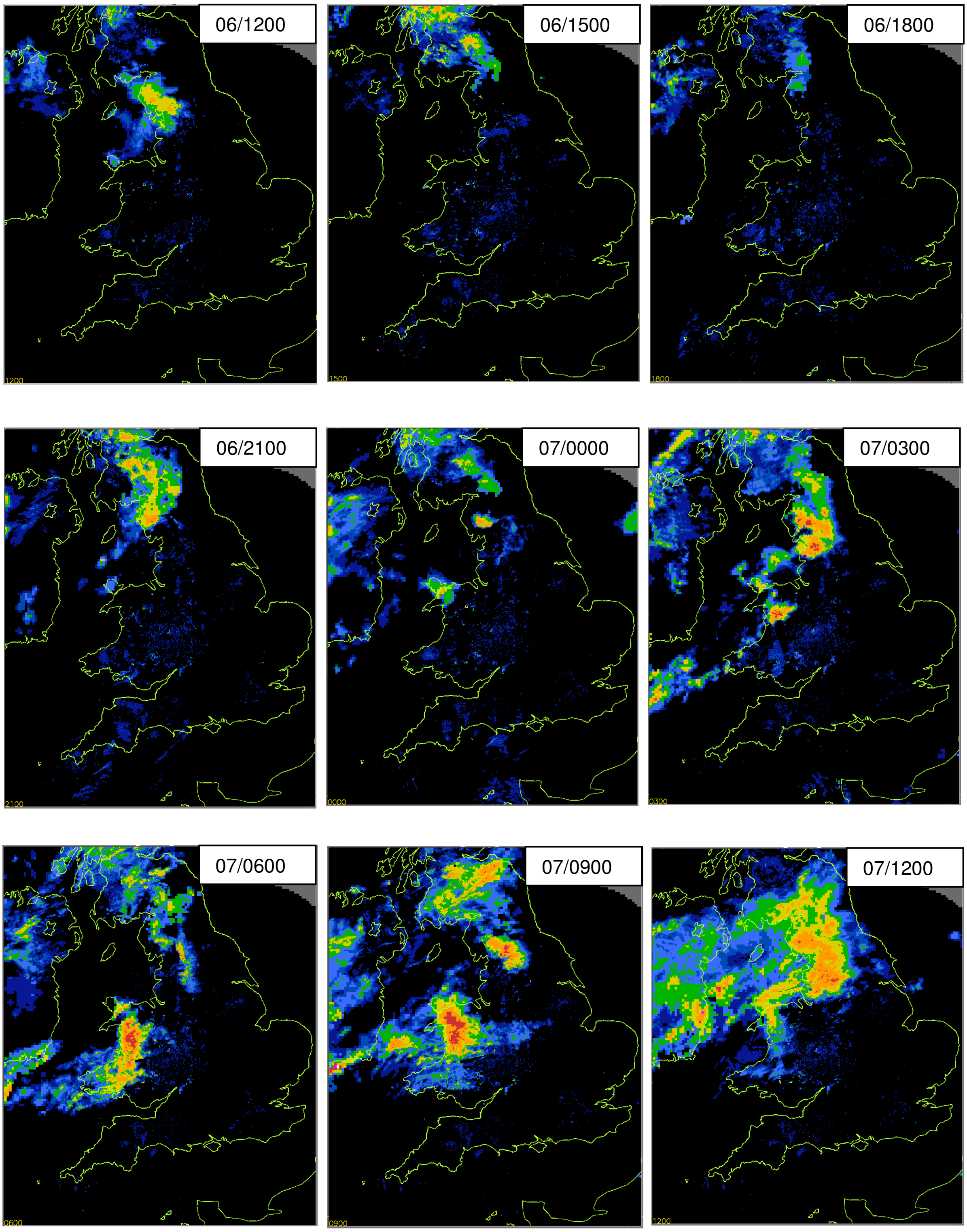
At 1200 UTC on 6 January moderate to heavy rain was falling over Cumbria. However, by 1500 UTC this rain had eased away northwards and remained light at 1800 UTC. By 2100 UTC a further pulse of heavy rain had reached Cumbria which subsequently shrank in size by 0000 UTC on 7 January before growing again by 0300 UTC. This growth/decay cycle was repeated up to 0900 UTC. However, unlike the previous times the rainfall was concentrated over the Pennines and the central part of the Lake District and not over the western up-slopes. Further south, rain began to turn heavy over the mountains of North Wales by 0300 UTC on 7 January and then intensified and became more widespread that morning. By 1200 UTC heavy rain was falling over most of NW England which became persistent and very heavy over the Cumbrian fells till just after midnight. At 0000 UTC on 8 January the cold front (Figure 3-4) was moving into the Irish Sea and the main rain area was to the east of the surface position of the front shown in Figure 3-4. The cold front was well delineated at 0300 UTC on 8 January by a narrow line of very intense rainfall rates stretching north-eastwards through Devon, across the Bristol Channel and over central Wales. Over Cumbria, the heavy rainfall was beginning to ease by this time. However, by 0600 UTC another area of heavy rain had spread in. This was associated with the occluded front wrapping itself around the deep depression over the Border region.

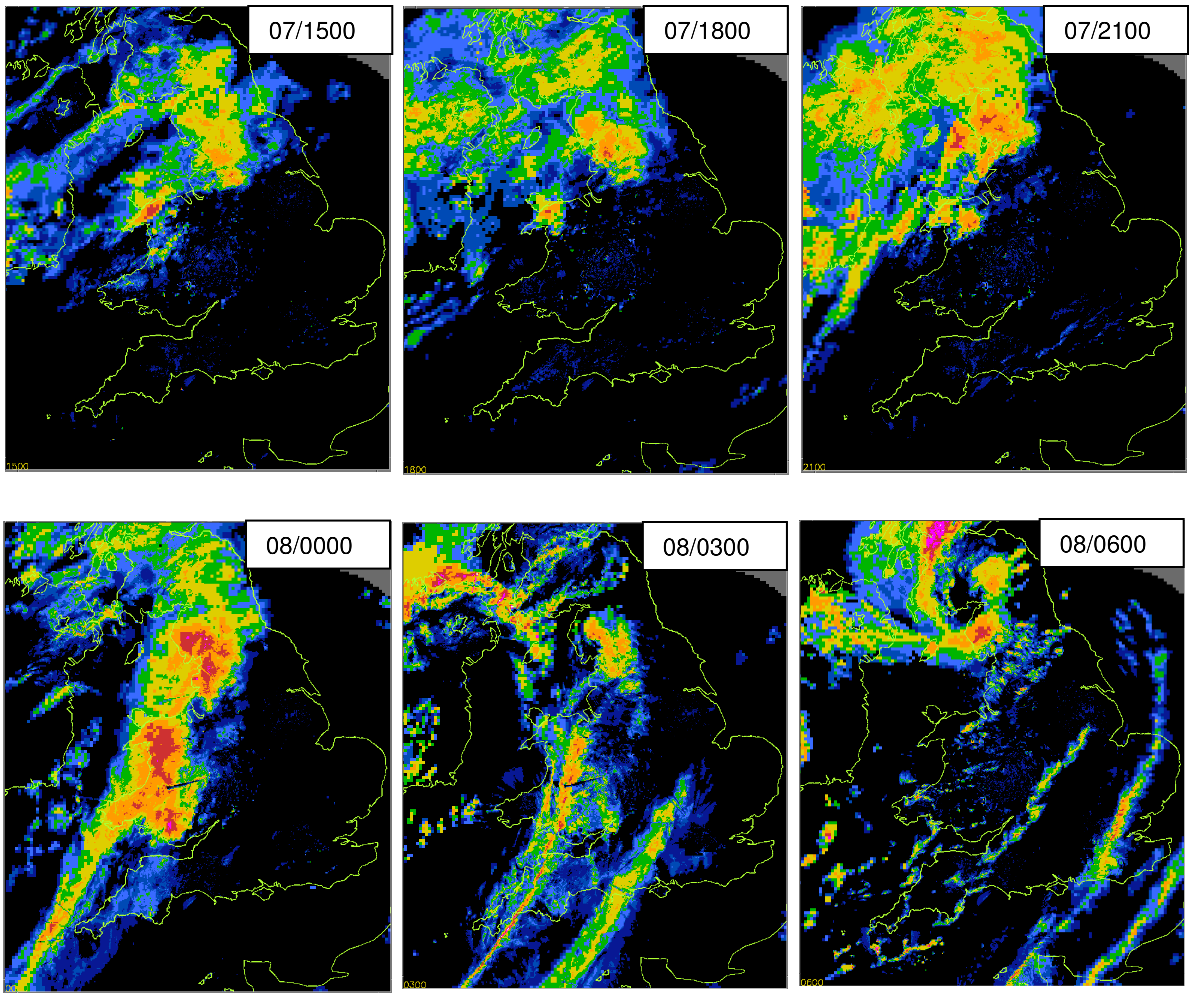
Figure 3-16: Map showing the circular edge of 2km resolution data coverage for Hameldon Hill radar which serves Cumbria, and its location in relation to all UK radars (shown bright in insert).



In order to explain the apparent “pulsing” of the rainfall over Cumbria before 1200 UTC on 7 January, charts showing wet-bulb temperature from Mesoscale Model analyses for a particular level have been produced and are shown in Figure 3-18. Wet-bulb temperature is a useful tracer for variations in the amount of water vapour the air can hold in a particular airmass. The higher the wet-bulb temperature the more water vapour it can hold and which is available for condensation into cloud droplets and eventually rain. The closer the air temperature is to the wet-bulb the more saturated the air is. In Figure 3-18 the temperature and wet-bulb temperature are shown for one level, 1600m asl, which is the same as used for relative humidity shown earlier. This obviously means that over high ground the level will be closer to the surface and will reflect modifications to the airmass due to the influence of topography.

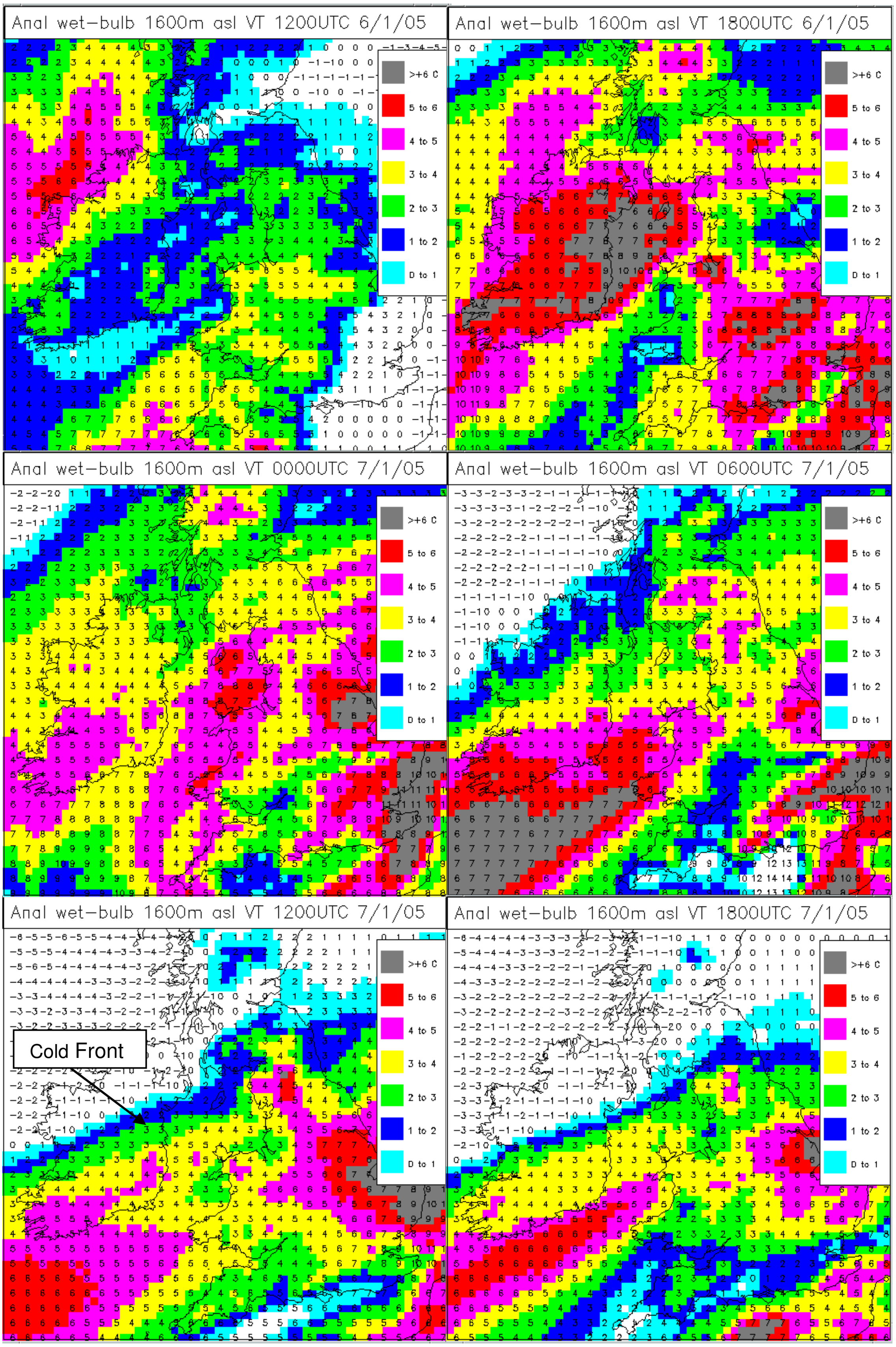
Figure 3-17: Met Office radar rainfall rates shown at three hourly intervals from 1200 UTC 6 to 0600 UTC 8 January. Displays are colour coded such that blue represents rainfall rates <1 mm/h, green 1-2mm/h, yellow 2-4mm/h, orange 4-8mm/h, red 8-16mm/h and magenta 16-32mm/h. Each image is a quality controlled composite from several radars designed to show returns at 1km resolution close to radar sites decreasing to 2km and 5km with increasing distance from the radars.

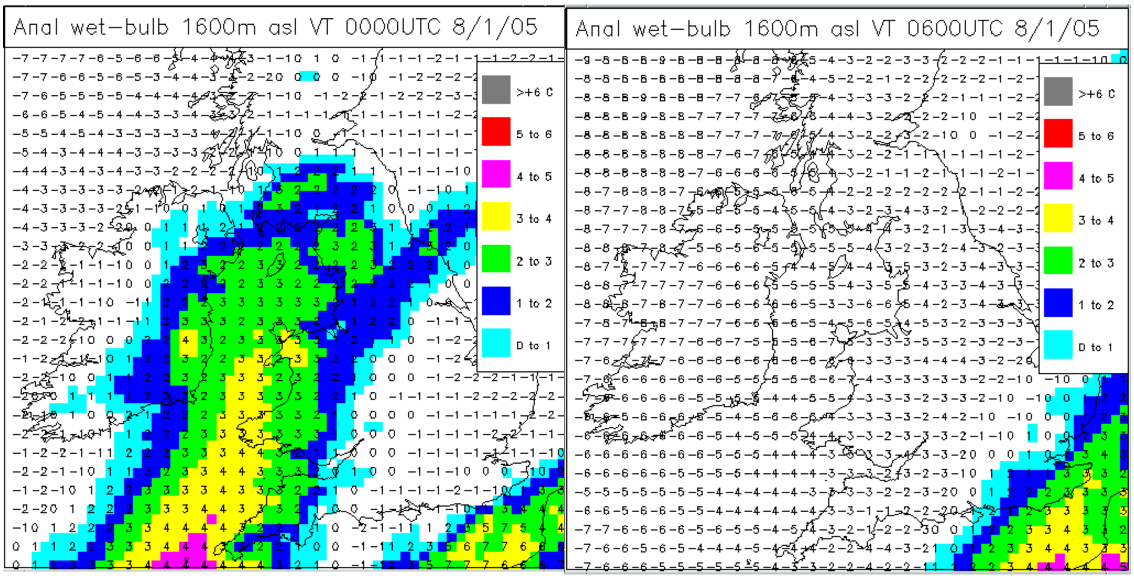




Between 1200 and 1800 UTC on 6 January the wet-bulb temperature in the western Irish Sea had increased by over five degrees. As this warmer air was lifted over the Cumbrian fells by the strengthening south-westerly wind that evening it produced an increase in low cloud cover (see Table 3-4) and heavy rain. Another pulse of warmer air came through just after midnight, however by 0600 UTC, air with a lower wet-bulb temperature, but still saturated with extensive low cloud, was advecting into the region and decreasing the rainfall intensity as shown by the radar comparing the 0300 and 0600 UTC images. However, at 0600 UTC wet-bulb temperatures were already rising again in the south-eastern Irish Sea and by 0900 UTC this warm and saturated air (moving northeast at about 70 knots) was causing heavy rain over the high Pennine region. By 1200 UTC 7 January the waving cold front had moved south to lie less than 100km from Cumbria. The location of the cold front is quite noticeable on the 1200 UTC wet-bulb temperature chart lying in a region of strong gradient with cold air to the north. The cold front rain can be seen in the radar pictures over Northern Ireland from 1800 UTC 6 January to 0900 UTC 7 January. By 0900 UTC the frontal rain was starting to get heavier and by 1200 UTC there were large areas of frontal rainfall greater than 0.5mm/hr moving into Cumbria with the seeder/feeder mechanism in full swing by this time. Very heavy rain then persisted all afternoon and evening in association with the waving cold front and feeder/seeder processes. Around 0000 UTC the cold front began to push through and the wind swung round to the west as the colder polar air (shown as blue and white in the wet-bulb temperature maps) began to push in.

Figure 3-18: Analysis of wet-bulb temperature at 1600m asl from the Met Office Mesoscale Model at six hourly intervals from 1800 UTC 6 January 2005 to 0000 UTC 8 January 2005. Actual temperatures are shown over-plotted as figures at every other grid point. The position of the cold front over Northern Ireland at 1200 UTC on 7 January is indicated.





3.3.5 Rain gauge data

Data from Environment Agency rain gauges over Cumbria have been analysed in this study. Information from the gauges is presented in
Table 3-5, ranked by rainfall total for the period of analysis 1200 6 January 2005 – 1200 8 January 2005.

Table 3-5: Environment Agency rain gauge information showing place and location, altitude (metres), 12 hourly totals from 1200 6 January 2005 to 1200 8 January 2005 and a 48 hour total for the whole period (50 highest recording gauges)

STATION NAME	EASTING	NORTHING	ALT. m asl	6 12-24	7 0-12	7 12-24	8 00-12	TOTAL
Honister	322500	513500	361	14.4	59.6	112.6	26.4	213.0
Wet Sleddale	355300	511600	277	7.6	76.8	79.4	43.0	206.8
Seathwaite Farm	323500	512100	-	9.4	43.2	106.6	34.0	193.2
BlackSail E'dale	319400	512500	-	10.8	47.8	102.2	30.6	191.4
High Snab Farm	322200	519000	-	9.4	29.6	104.0	37.2	180.2
Thirlemere	331300	519500	164	11.2	48.0	79.6	40.0	178.8
St Johns Beck	613000	695000	-	11.2	47.8	79.6	40.0	178.6
Burnbanks	350750	515920	222	9.8	57.2	70.0	39.8	176.8
Brothers Water	339900	513900	164	8.6	69.0	66.2	32.0	175.8
Tow Hill	383000	486700	-	3.6	62.0	79.6	24.0	169.2
Orton Shallowford	362600	508300	-	6.2	64.0	72.8	23.4	166.4
Dale Head	331300	517500	187	10.2	41.0	80.6	30.8	162.6
Moorhall Farm	349400	518150	-	6.0	38.0	65.8	41.0	150.8
Aisgill Tel	377800	496300	365	6.4	48.2	68.6	19.0	142.2
Elterwater	332900	503900	72	2.8	34.2	76.2	22.0	135.2
High Row	338625	522355	-	7.0	41.2	53.8	33.0	135.0
Mosedale	335640	532150	226	8.0	31.0	49.6	43.0	131.6
Kentmere Hallowbank	346600	505400	266	2.6	28.8	62.6	37.0	131.0
Scalebeck	367300	514400	176	4.2	42.6	52.8	30.4	130.0
Mungrisedale	336000	527800	-	8.4	32.2	51.6	35.0	127.2
Beckermonds	387360	483070	-	2.4	44.8	60.6	15.8	123.6
Sedburgh	367700	491800	134	4.4	35.8	70.2	13.2	123.6
Brathay Hall Tel	336600	503200	51	3.4	31.2	67.4	18.2	120.2
Skelton Tel	343600	536100	207	7.6	31.4	45.4	32.8	117.2
Far Gearstones	378300	480100	311	3.0	44.4	55.2	13.6	116.2

Alston S Works	371400	547400	-	1.4	21.8	59.4	27.8	110.4
Hartside	366800	542300	-	2.2	19.6	57.2	28.2	107.2
Knarsdale	366600	553100	-	2.2	19.6	57.2	28.2	107.2
Wastwater Hotel	318700	508700	-	1.4	19.0	76.0	10.6	107.0
Watchgate	353200	497900	196	3.6	25.6	64.4	13.2	106.8
Footholme	365300	453300	169	0.4	26.2	59.4	18.8	104.8
Calebreck Hall	334500	536100	-	5.0	19.8	48.0	31.8	104.6
Sedbusk	388400	491080	-	2.2	33.2	44.6	24.2	104.2
Portinscale	325120	523900	77	6.8	22.0	67.0	7.8	103.6
Stocks Farm	371700	454800	193	0.4	25.8	53.4	17.6	97.2
Coalburn Whitehill	369400	577800	275	3.8	27.0	45.6	20.2	96.6
Clapham Turnerford	372200	466100	-	0.4	29.0	49.8	16.6	95.8
Greenhills Farm	383823	532004	-	2.0	20.6	54.2	17.6	94.4
Cornhow	315000	522200	98	4.0	13.2	60.4	16.4	94.0
Green Close Farm	342600	526500	246	4.8	20.2	38.6	25.2	88.8
Quarry Hill	321900	541200	145	6.0	18.4	45.2	18.2	87.8
Haltwhistle	368000	564000	-	5.0	23.6	38.0	20.2	86.8
Kielder Ridge End	365800	595900	-	5.0	23.6	38.0	20.2	86.8
Braidlie			-	8.0	25.2	37.2	15.4	85.8
Starling Gill	313600	515300	-	3.8	11.2	56.2	12.2	83.4
Solwaybank			-	9.2	14.6	40.8	11.6	76.2
Newton Rigg	349300	531000	-	4.2	12.2	35.6	23.8	75.8
Brackenber	372200	519500	-	1.4	15.4	35.2	23.6	75.6
Ennerdale WTW	308400	515400	111	2.4	6.8	55.4	9.6	74.2
Wiley Sike Gland	364500	570500	-	3.0	13.6	44.6	12.4	73.6

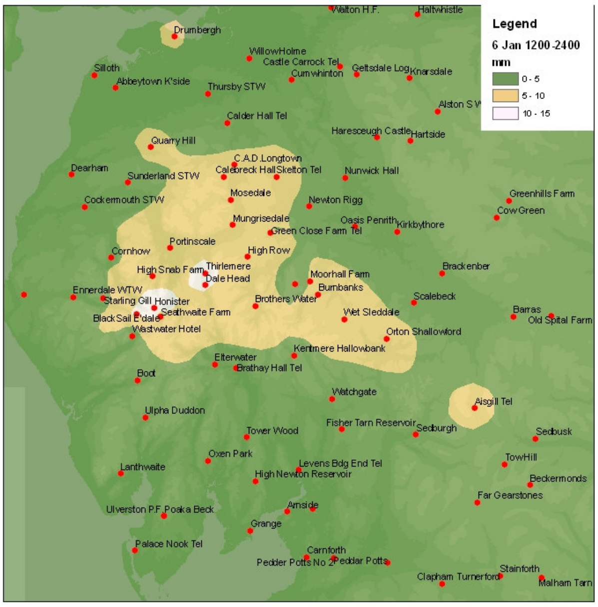
The rain gauges each show a similar time sequence of rainfall accumulation, with the maximum in the second half of 7 January. The influence of orography is clearest in the previous accumulation period (00Z-12Z on 7 January). However, overall, the totals reflect a very coherent distribution arising from the effects of altitude, shelter and distance from the sea, as well as random elements arising from the convective storms associated with the passage of the depression. The maximum recorded overall accumulation occurred at Honister, and was 213mm in two days. As will be shown in Section 3.5, the maximum sustained rates were around 22mm/hr and an average of 9mm/hr was sustained for 12 hours. It is this sustained heavy rain over a long period that resulted in the flooding.

Figure 3-19: Location and altitude of rain gauge sites

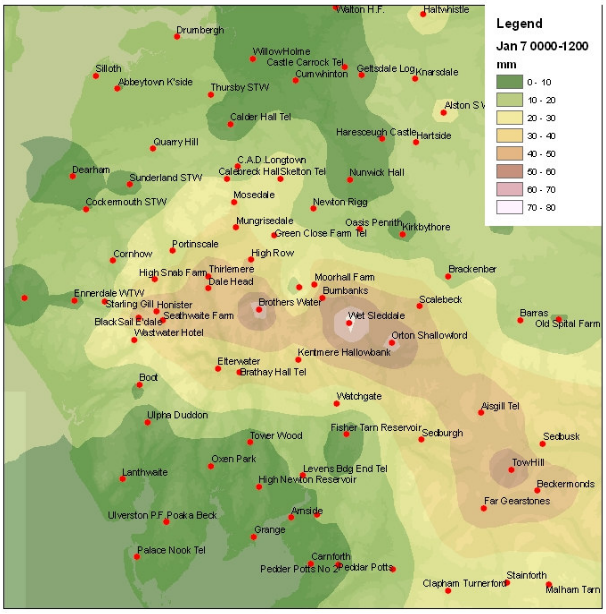
Raingauge Locations (OS 50m Panorama)

Figure 3-20: Rainfall accumulations for the periods 1200 6 January→ 2400 6 January (contour interval is 5mm/hr), 0000 7 January →1200 7 January (contour interval is 10mm/hr), 1200 7 January →2400 7 January (contour interval is 10mm/hr) and 0000 8 Jan→1200 8 January (contour interval is 5mm/hr). The total precipitation over the whole period (1200 6 January → 1200 8 January) is also shown, with a contour interval of 25mm/hr.

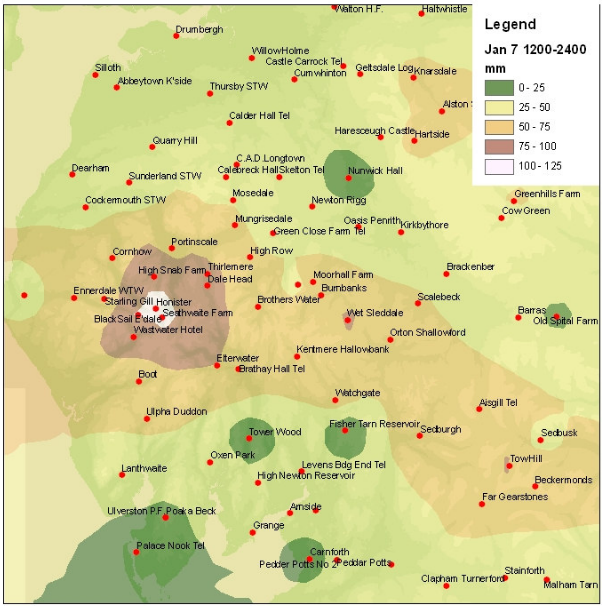
Rainfall Depth Jan 6 1200 - 2400



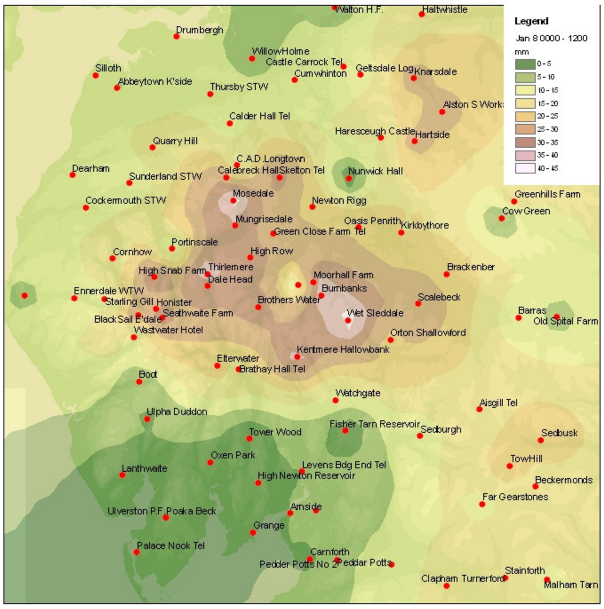
Rainfall Depth Jan 7 0000 - 1200



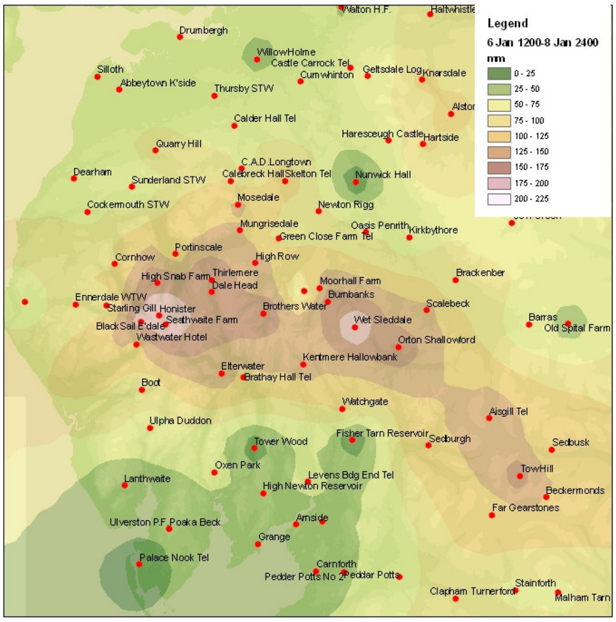
Rainfall Depth Jan 7 1200 - 2400



Rainfall Depth Jan 8 0000 - 1200



Rainfall Depth Jan 6 1200 - Jan 8 1200



3.3.6 Summary

- The rainfall event that generated the flooding in Cumbria was caused by a strong airflow of unusually warm, moist tropical air, forced northwards ahead of an Atlantic cold front, over a period of nearly three days. At the end of this period, the rainfall was enhanced by strong frontal uplift and convection, as a depression centre passed nearby to the north of the area.
- During the initial period, the rainfall enhancement is well described by the seeder/feeder process. In the last period, the distribution was complicated by the frontal and convective elements.
- Research suggests that the shape of the vertical wind profile may have contributed to the orographic enhancement.
- The maximum observed rainfall was 213mm at Honister. Peak 15min rates were between 20-30mm/hr, but high rates were sustained over an exceptionally long period.

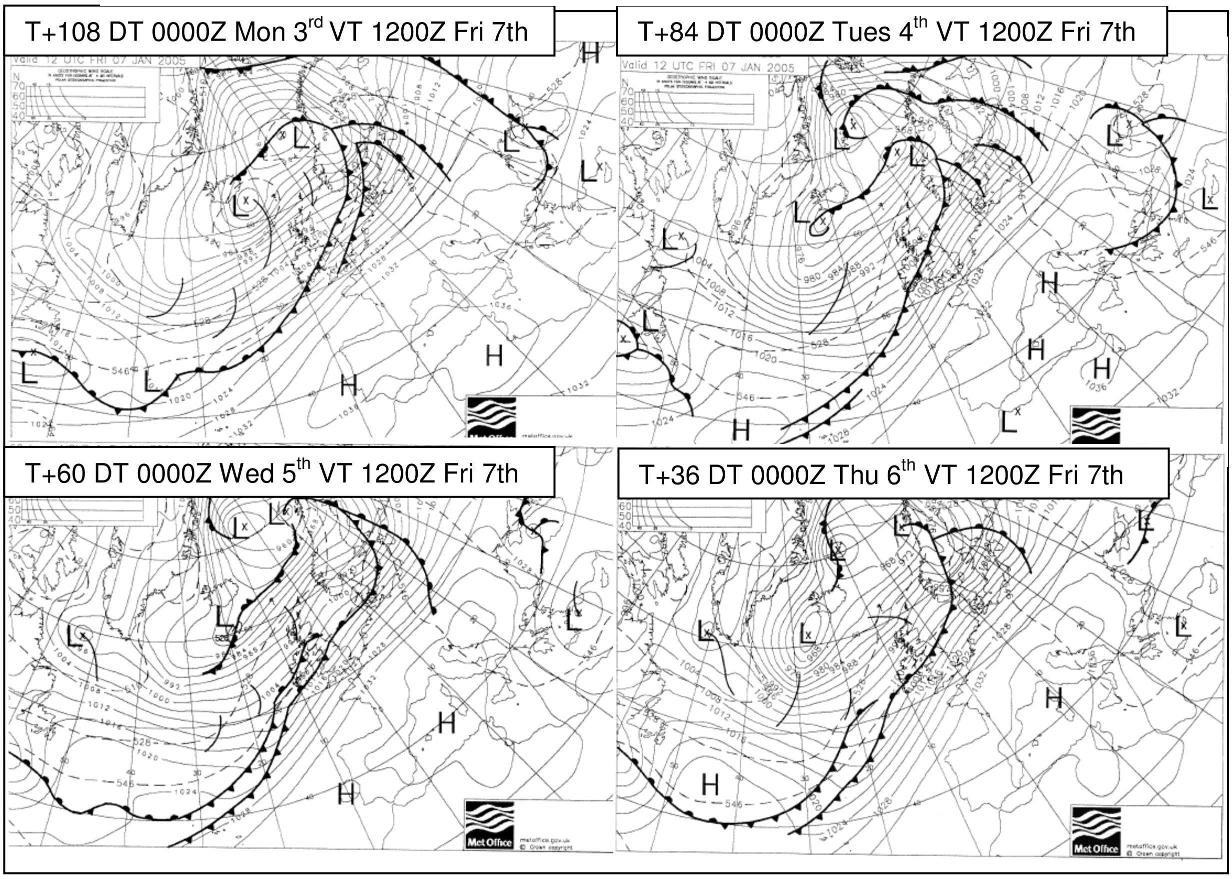
3.4 Forecasts of the event

Two forecast ranges are considered in this report. Forecasts more than six hours ahead which would concentrate on getting the emphasis and conditions correct for Cumbria as a whole, forecasts up to six hours ahead where it is expected that local detail would be given.

3.4.1 Weather Forecasts more than 6 hours ahead

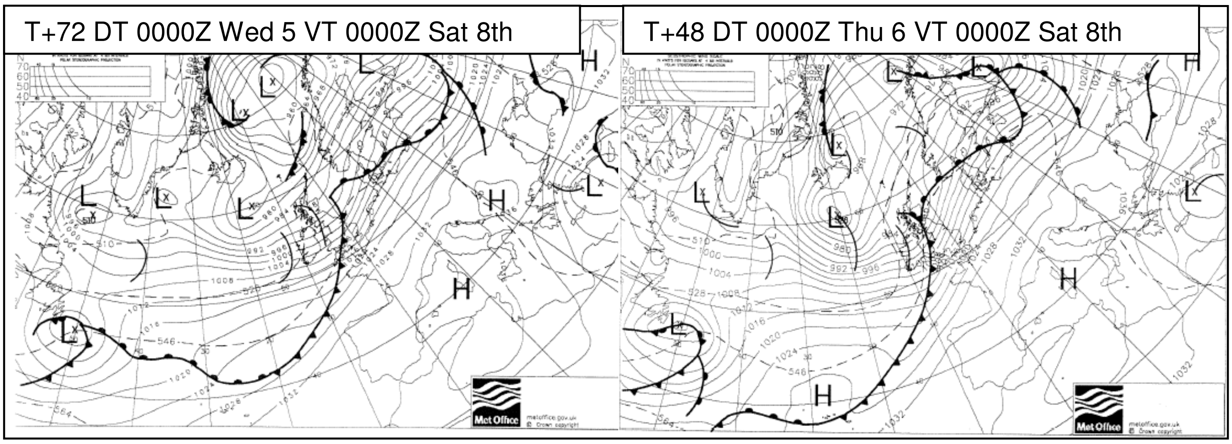
Forecast charts of mean sea-level pressure prepared by the Chief Forecaster in the Met Office at Exeter are shown in Figure 3-21 and Figure 3-22. The forecasts are based on a skilled interpretation of all available numerical model outputs from several centres around the world. Figure 3-21 shows forecasts for 1200 UTC on Friday 7 January made at 0000 UTC on Monday to Thursday.

Figure 3-21: Maps showing Met Office forecasts of mean sea-level pressure isobars and fronts for 1200 UTC 7 January 2005. Forecast lead times are 108, 84, 60 and 36 hours which were based on data at 0000 UTC on 3, 4, 5 and 6 January respectively.



If these forecast charts are compared with the analysis chart for 1200 UTC 7 January 2005 shown in Figure 3-4 it can be seen that all the forecasts have low pressure near Iceland, an anticyclone in the Mediterranean area and a cold front crossing the UK with a warm and moist tropical south-westerly air flow ahead of it. The worst forecast was the one made on Monday 3 which has pushed the cold front too far south cutting off the south-westerly and orographic rainfall too quickly. The reason for this is probably the lack of frontal waves which are evident on the analysis and other forecast charts. The best forecasts were those made on Tuesday 4 January and Thursday 6 January. The forecast made on Wednesday 5 January again has the cold front slightly too far south into North Wales. A more detailed analysis was carried out in the internal report May et al (2005). Copies of the report are available on request.

Figure 3-22: Maps showing Met Office forecasts of mean sea-level pressure isobars and fronts for 0000 UTC 8 January 2005. Forecast lead times are 72 and 48 hours which were based on data at 0000 UTC on 5 and 6 January respectively.



This error is continued 12 hours later in the forecasts for 0000 UTC on the 8 January shown in Figure 3-22. The cold front is too far south and east in the Wednesday forecast. However, the forecast made on Thursday is better but still has the cold front too far east and also has not developed the new low to the west of Ireland, which none of the previous forecasts captured either. All of the forecast errors were relatively small on a global scale but did impact on the issued weather forecasts. The Daily Weather Forecasts issued to the Environment Agency North West Region in the days leading up to 7 - 8 January 2005 identified the potential for unsettled weather with showers or longer periods of rain accompanied by strong winds. These Daily Weather Forecasts are included as Appendix 1.

The forecast issued on Monday 3 January reflected the expected faster progress of the cold front over Cumbria by stating for Friday: "*Rain clearing during the morning then sunshine and blustery showers. Very windy*". Clearly quite wrong in emphasis and expected type and duration of rainfall.

The Tuesday forecast for Friday 7 January read: "*Cloudy with rain at times. Gales in places.*" This was much better and clearly reflected the slower advance of the cold front and strong winds in the warm south-westerly air flow. For Saturday 8 the forecast read: "*Windy with blustery showers*", again hinting at a faster clearance of the cold frontal rain than actually occurred.

The forecast issued on Wednesday 5 for Friday read "*Occasional southwest gales. Rain, heavy and persistent, especially on southwest slopes of the Lake District with some substantial totals likely (120mm at Honister). The rain giving way to blustery showers in the evening.*" This was an excellent forecast showing that the numerical models were, by this stage predicting substantial amounts of moisture available for precipitation generation both in the warm south-westerly and in the cold frontal zone. The forecast chart showed a double frontal structure indicative that the southern front would be delineating the northern boundary of some very warm and moist air. However, the forecast was again too fast in clearing away the persistent rain.

On Thursday 6 January the predicted 24 hour rainfall accumulation for Cumbria and the Pennines, north of the Ribble, for the period 0000 UTC on 7 January to 0000 UTC on 8 January was 45mm. At this stage Met Office forecasters would have been guided by outputs from the Mesoscale Model which has a grid spacing of approximately 12km. Some model forecasts of rain and wind are shown in Figure 3-23 and Figure 3-24.

Figure 3-23: Left column shows rainfall accumulation forecasts from the Met Office Mesoscale Model for period 0300 to 1500 UTC 7 January 2005 from data at 0600,1200 and 1800 UTC 6 January 2005. Corresponding 610m wind forecasts for 1200 UTC 7 January 2005 are shown in the right column – see key adjacent to Figure 3-8.

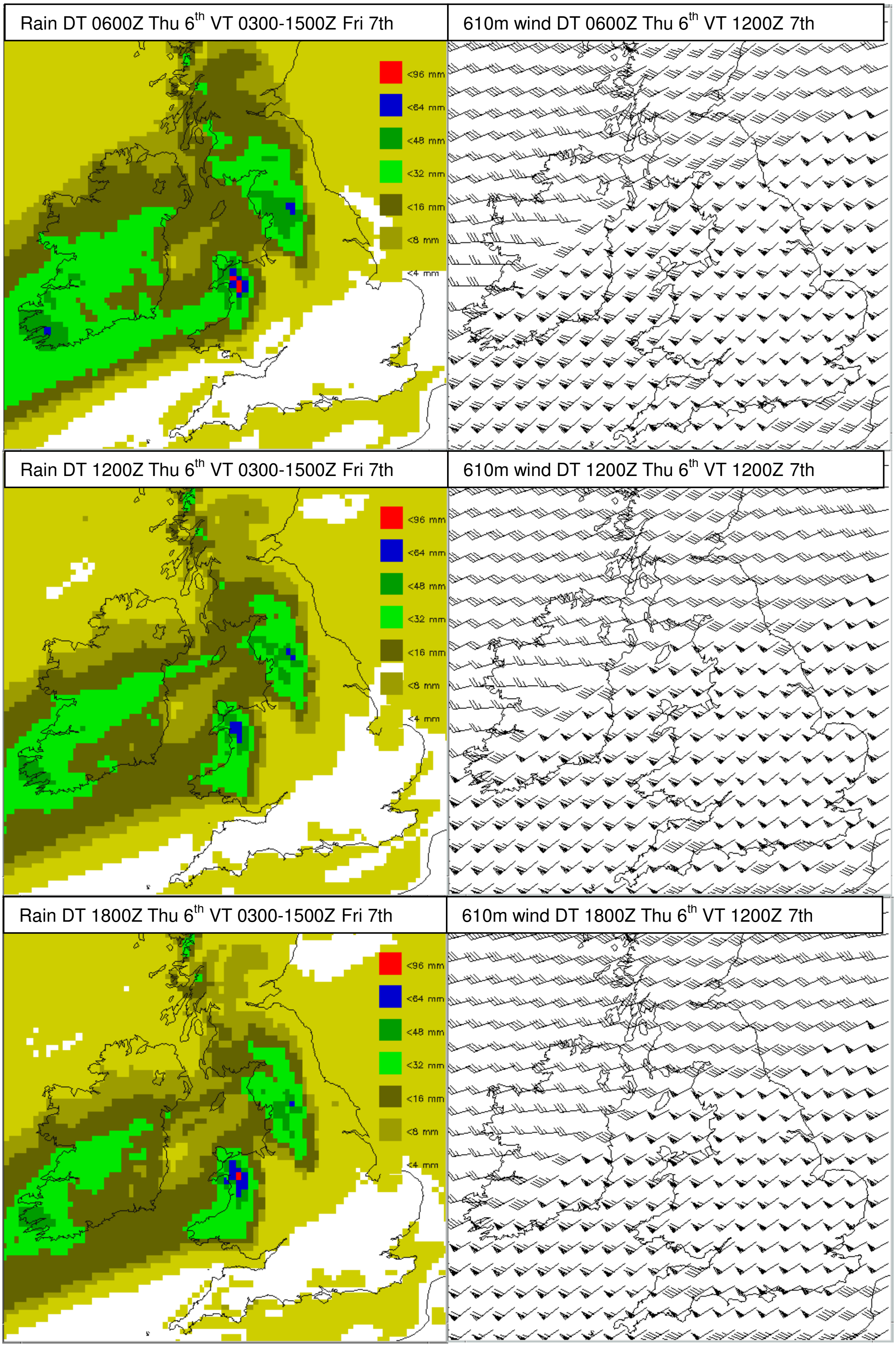
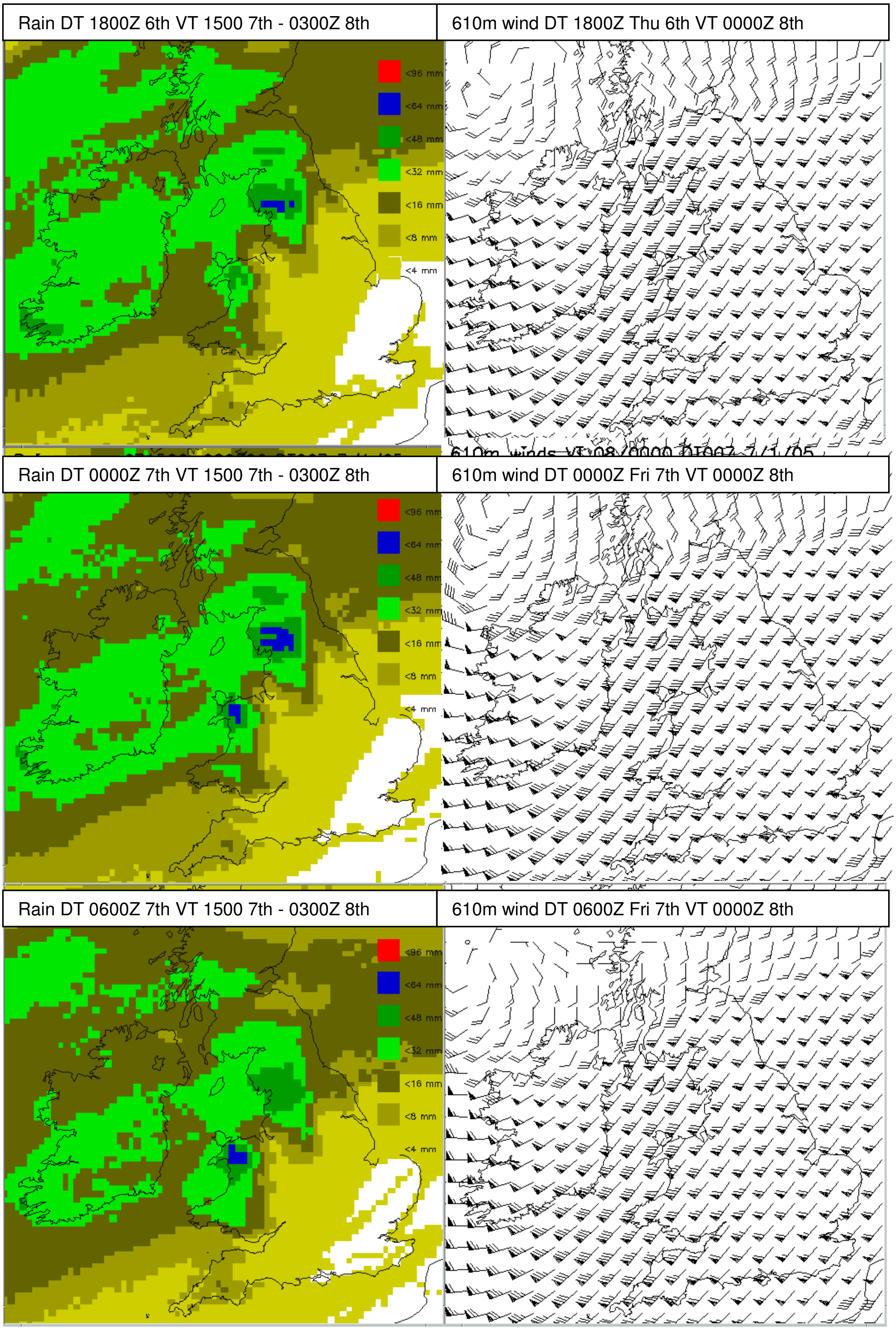


Figure 3-24: Left column shows rainfall accumulation forecasts from the Met Office mesoscale model for period 1500 UTC 7 January 2005 to 0300 UTC 8 January 2005 from data at 1800 and 0000 UTC on the 6 January and 0600 UTC 7 January 2005. Corresponding 610m wind forecasts for 0000 UTC 8 January 2005 are shown in the right column- see key adjacent to Figure 3-8.



Winds are plotted at alternate grid points in Figure 3-23 and Figure 3-24. In Figure 3-23 the rainfall forecasts for the period 0300 to 1500 UTC on 7 January are very similar with orographically enhanced rainfall over the Lake District and mountains of North Wales. In the forecast from 0600 UTC 6 January the rainfall in the range 32-48mm is more extensive than in the later forecasts. That was possibly due to stronger predicted wind speeds at 1200 UTC 7 January in that run. In Figure 3-24 the rainfall forecasts for 1500 UTC 7 January to 0300 UTC 8 January are also quite similar. However, the latest forecast from data at 0600 UTC has less rain than the previous two. All of the forecasts in this period correctly predicted the strengthening of the low-level wind ahead of the cold front at 0000 UTC 8 January (comparing with Figure 3-9), although the winds in the run from 1800 UTC 6 January were 5 to 10 knots too strong in the Irish Sea.

The forecast issued at 0940 UTC on Friday 7 January said that the active frontal zone would remain slow moving but would clear the region during the early hours of Saturday. It predicted a rainfall accumulation of 90mm for Cumbria and the Pennines north of the Ribble for the 24 hour period ending 0000 UTC on Saturday 8 January. In reality rainfall accumulations of up to 163mm were recorded by rain gauges in this area between 0000 UTC on 7 January and 0000 UTC on 8 January 2005 (see
Table 3-5).

It is clear that although the Daily Weather Forecasts issued to the Environment Agency North West Region in the days leading up to 8 January 2005 did identify the potential for periods of heavy rain leading to substantial accumulations, they did not predict the magnitude of rainfall totals that actually occurred.

Using Mesoscale Model outputs as a guide, Met Office Manchester issued a Heavy Rainfall Warning to the Environment Agency North West Region at 1529 UTC on Thursday 6 January. This is included as Appendix 1. The wording of this warning made it quite clear that there was potential for unusually large accumulations of rainfall. Southwest facing slopes of high ground were forecast to get most rain. In particular, Honister was expected to receive a 24 hour accumulation of 120mm with a 30% risk of 150mm. More generally, forecast rainfall totals were divided into two 12 hour periods: between 0300 UTC and 1500 UTC on 7 January, when an average of 20mm was predicted with a possible maximum of 50mm; and between 1500 UTC on 7 January and 0300 UTC on 8 January, when an average of 30mm was forecast with a maximum of 70mm. Table 3-6 provides details of rainfall accumulations for these two 12 hour periods from Environment Agency rain gauges distributed throughout the area. Whilst it is evident that it was not only rain gauges on south-west facing slopes that received 24 hour accumulations in the vicinity of 120mm, the outcome was nevertheless consistent with the forecast indication that significant areas would receive 24 hour accumulations in the upper part of the 70-120mm range, as well as with the forecast peak value at Honister.

Table 3-6: Rainfall accumulations as recorded by selected Environment Agency rain gauges distributed throughout the Eden Catchment area for the 12 hour periods (i) from 0300 UTC to 1500 UTC on 7 January 2005 and (ii) from 1500 UTC on 7 January 2005 to 0300 UT

Rain gauge	Grid reference	Altitude (m)	Rainfall accumulation (mm) recorded over 12 hour period	
			(i) ending 1500 UTC 7 January 2005	(ii) ending 0300 UTC 8 January 2005
Aisgill Moor	SD778963	365	64.6	56.6
Barras	NY845121	343	20.0	29.4
Brotherswater	NY399121	164	55.2	73.6
Burnbanks	NY507160	222	50.2	82.8
Green Close Fm	NY426265	246	21.4	38.2
Honister	NY225135	361	45.6	100.2
Scalebeck	NY673144	176	39.8	64.2
Willow Holme (Carlisle)	NY389565	17	14.0	24.4

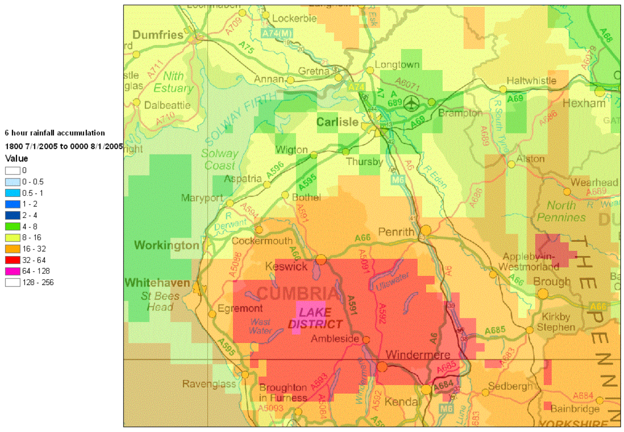
3.4.2 Weather forecasts up to six hours ahead

These were based on outputs from the automatic Met Office Nowcasting systems Nimrod and Gandolf. Both Nimrod and Gandolf would have been expected to perform well in this case, provided that the Mesoscale Model predictions of the timing and extent of the frontal precipitation were reasonably accurate. This is because the areas of maximum accumulation were dominated by orographically enhanced precipitation, and both precipitation nowcast algorithms incorporate an orographic enhancement scheme based upon that proposed by Alpert and Shafir (1989). A time series of enhancement fields are estimated from the Mesoscale Model forecasts of boundary layer (low-level) horizontal wind and a high resolution Digital Terrain Model (DTM). The enhancement field estimated at observation time is subtracted from the rain analysis field (Bowler *et al*., 2004). The extrapolation component of the nowcast is performed on the residual field, and appropriate enhancements are added back after extrapolation, but only where precipitation is predicted. This methodology is consistent with the seeder-feeder process discussed in Section 3.3.3.

Figure 3-25 compares six hour accumulations predicted by Nimrod, Gandolf and the Mesoscale Model for the period starting at 1800 UTC on 7 January 2005 with the equivalent six hour accumulation estimated directly from a 15 minute resolution sequence of quality controlled, 2km composite radar data. The latter produces estimates of surface accumulation in excess of 32mm over the mountains of north-west England, and between 16mm and 32mm over larger areas of northern England and the southern uplands of Scotland. The equivalent Gandolf and Nimrod six hour accumulation nowcasts (2km and 5km horizontal resolution respectively) compare well with the radar estimates in terms of both the extent and severity of the event in the wettest areas. However, the area of accumulation in excess of 32mm is slightly smaller than that inferred from quality controlled radar data. For comparison, the Mesoscale Model also picks up the potential for accumulations greater than 32mm over the high ground of north-west England. The 0000 UTC run of the Mesoscale Model on 7 January 2005 identifies two areas where accumulations are expected to be more than 32mm, one between Keswick and Ambleside and the other near Kirkby Stephen, whereas the run made 12 hours later focuses the highest predicted accumulations close to Ambleside.

Generally, Nimrod, Gandolf and the Mesoscale Model, which included significant corrections due to orographic enhancement, performed well in predicting rainfall for this relatively large-scale system but with a tendency to under-predict the 6hr accumulations. This is supported by research which suggests that the method used to capture orographic enhancement in the Nimrod and Gandolf forecast systems may under-estimate the peak rates, especially when potential instability leads to orographic triggering of convection.

Figure 3-25: Comparison of six hour accumulations for the period starting 1800 UTC on 7th January 2005 produced by aggregation of quality controlled radar estimates of surface rain rate (top-left), Gandolf (middle-left) and Nimrod (middle-right) nowcasts and from two runs of the Mesoscale Model, made at 0000 UTC on 7 January 2005 (bottom left) and at 1200 UTC on 7 January 2005 (bottom right).



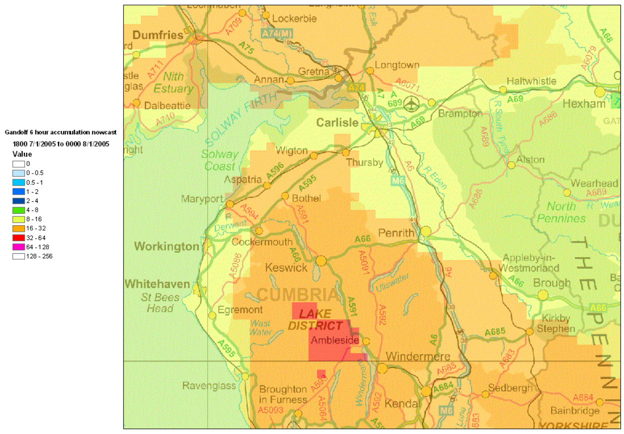
Top-left: 6 hour accumulation from Nimrod radar composite for the period starting 1800 UTC on 7 Jan 2005

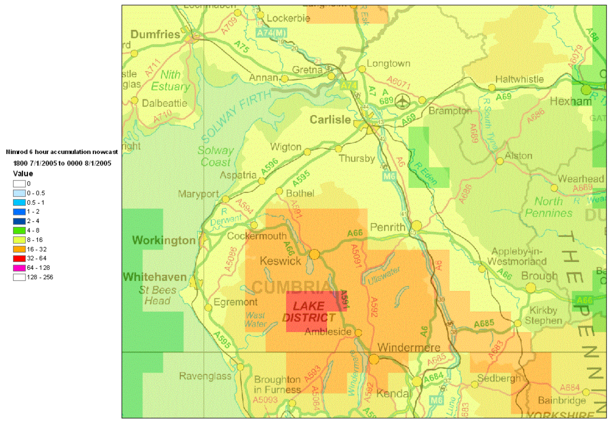
Middle-left: Gandolf 6 hour accumulation nowcast for the period starting 1800 UTC on 7 Jan 2005

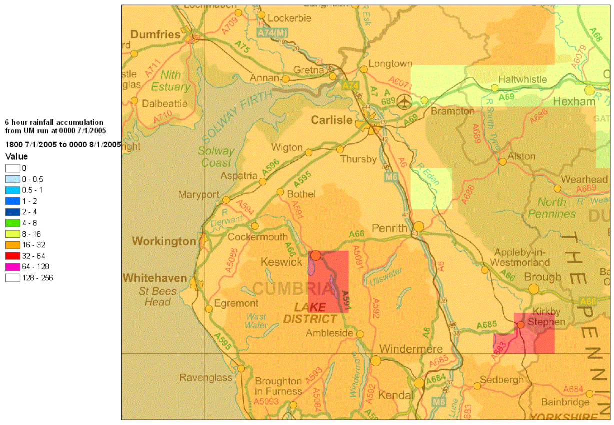
Middle-right: Nimrod 6 hour accumulation nowcast for the period starting 1800 UTC on 7 Jan 2005

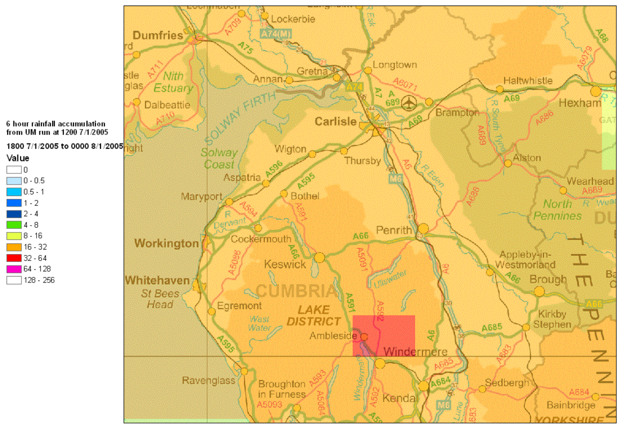
Bottom-left: Mesoscale Model 6 hour accumulation forecast for the period starting 1800 UTC on 7 Jan 2005 from model run at 0000 UTC on 7 Jan 2005

Bottom-right: Mesoscale Model 6 hour accumulation forecast for the period starting 1800 UTC on 7 Jan 2005 from model run at 1200 UTC on 7 Jan 2005









3.4.3 Forecasts from the Extreme Rainfall Event Recognition Project

In addition to the standard Daily Weather Forecasts and Heavy Rainfall Warnings, the Met Office was also generating trial Extreme Rainfall Forecasts as part of a research project. These forecasts were issued once per day during the morning to Environment Agency Regional Managers in the Thames, SW and NW Regions. The forecast for this day has been re-run using up-to-date statistics and the latest version of the trial software. The re-run simplifies the output but has not changed the forecast outcome which was basically a “near miss”.

The NW Region Area forecasts and the corresponding largest fractions of the Phase 1 Extreme Rainfall threshold observed by radar are shown in Table 3-7.

Table 3-7: NW Region Area forecasts of the probability of getting extreme rainfall somewhere in each Area

Area	Highest Catchment Forecast probability in Area (%)	Largest fraction of the Extreme Rainfall threshold observed by radar (%)
North	4	104
Central	7	73
South	14	94

Note: The largest fraction of the Phase 1 extreme rainfall threshold observed by radar in the Area is shown in the last column.

Table 3-7 shows that all areas of NW Region had very heavy rainfall observed by radar with an extreme fall in the North Area. Unfortunately it was only the South Area that had a forecast probability greater than 10% (which in the context of that project was significant). This was, therefore, a “near-miss”. A set of 50 forecasts (known as an ensemble) from perturbed analyses from the European Centre for Medium Range Weather Forecasts (ECMWF) were used to calculate the severity of likely conditions for orographic enhancement of rainfall. In a substantial number of the ensemble members the front was slightly too far south thus cutting off the supply of warm moist air over the North Area early in the forecast.

Catchment probability forecasts in North Area (where Carlisle is located) have been reproduced in Table 3-7. The extreme rainfall forecast in Lower Eden Catchment was “NIL”, which was good as that catchment is relatively low-lying. However, all other catchments were forecast to get at least 152mm during the 24 hour period but with very low probabilities of these extreme rainfall values actually occurring. Similar low probabilities were also predicted at other times in the trial (when no extreme rainfall occurred) meaning that the reliability of the trial forecasts is questionable. Three catchments; Derwent, Greta and Eden all collected an extreme rainfall (according to radar data) during the forecast period. It is interesting that the forecast probability of extreme rainfall was the highest in these catchments but still very low overall.

In this event the Extreme Rainfall Forecast, correctly went for orographic enhancement rain up to 0000 UTC on 8 January and then correctly turned it convective. It did identify the Eden catchment as having the highest extreme rainfall probability, but detailed amounts were incorrect and it over-forecast in the south (Dane and Mersey catchments).

Table 3-8: NW Region - probability of Extreme Rainfall Catchment forecasts for North Area

Catchment	Forecast period	Probability (%)	Forecast Amount (mm)	Radar actual (mm)
Esk/Irthing	07/1200 – 08/1200	2	152	50
Lower Eden	NIL	-	-	-
Wampool/Ellen	07/1200 – 08/1200	2	152	63
Petteril/Caldew	07/1200 – 08/1200	2	152	88
Middle Eden	07/1200 – 08/1200	2	152	70
Derwent	07/1200 – 08/1200	4	152	158
Greta/St Johns	07/1200 – 08/1200	4	152	158
Lowther/Eamont	07/1200 – 08/1200	2	152	135
Upper Eden	07/1200 – 08/1200	2	152	102
Ehen/Calder	07/1200 – 08/1200	4	152	158
Duddon	07/1200 – 08/1200	2	152	129
Brathay/Rothay	07/1200 – 08/1200	2	152	126
Kent/Bela	07/1200 – 08/1200	3	152	127

Note: Table shows probability and amount of extreme rainfall. The largest rainfall observed by radar in the catchment is shown in the last column.

3.4.4 Summary

- The model forecasts captured the event well, in general, but details of the frontal position and timing remained uncertain until about 24 hours before the event. Model rainfall accumulations were substantial, but significantly lower than observed. Daily weather forecasts followed the model guidance.
- Nimrod and Gandolf forecasts performed well, but still with a tendency to under-predict the 6hr accumulations.
- The heavy rainfall warning issued at 1529 on 6 January provided excellent guidance.
- The Extreme Event Recognition Project algorithm failed to identify a high risk of extreme rainfall for this event.
- Research suggests that the method used to capture orographic enhancement in the Nimrod and Gandolf forecast systems may under-estimate the peak rates, especially when potential instability leads to orographic triggering of convection.

3.5 Rarity of the meteorological conditions

The Extreme Event Recognition project has identified 10 extreme rainfall events of the orographic type during the 20th Century. None of these actually occurred over Cumbria, but given the size of the area, and an expectation that the required strong low level winds are more likely in northern, rather than southern Britain, we would estimate a return period of between 50-100 years (2% - 1%) from this evidence. As part of the project, the conditions supporting such events were summarised as: strong low-level wind (>25m/s) from a south-westerly direction; originating from a region with high surface dew point (>14°C). The probability of obtaining this was estimated from model data at about 0.00014 per day. All cases were associated with an anticyclone close to Spain, and a low pressure system near Iceland, but only half had a slow-moving cold frontal system in the vicinity (within 100km) for at least 12 hours. This indicates a probability of about 0.00007 per day, or a 50 year return period (2%).

3.5.1 Rainfall Rarity

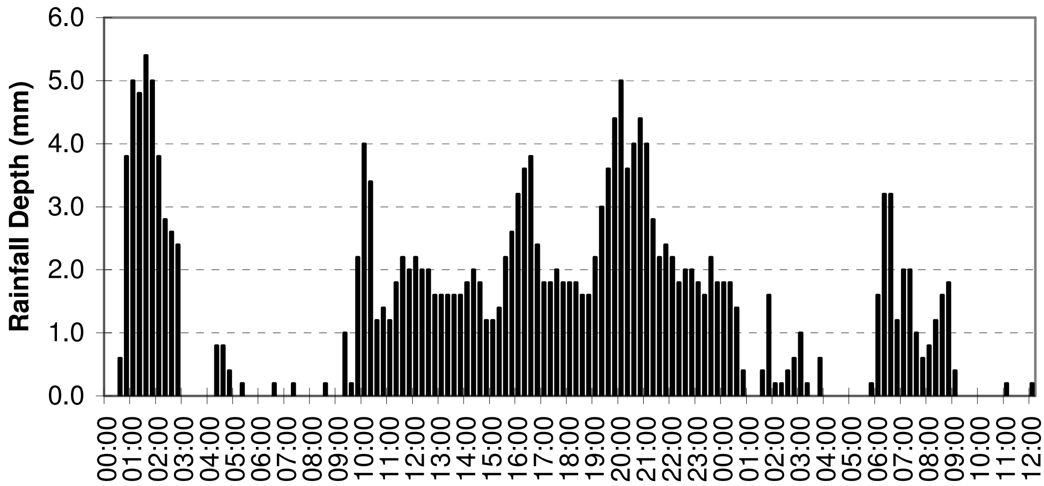
The rainfall rarity (or frequency) was assessed for a selection of rain gauges recording the highest rainfall for a range of return periods. The highest recording gauges over the

period 0000 6 January to 1200 8 January 2004 are shown in
Table 3-5. The highest recorded rainfall was at Honister and Wet Sleddale, 361 and 277m above mean sea level respectively.

For these gauges, rainfall frequency was assessed for the whole period, for 12 hour sub-divisions, and for particularly intense periods using the Flood Estimation Handbook methodology (Institute of Hydrology 1999).

At Honister, 213mm was recorded between 6 and 8 January, most of which occurred between midnight on 6 January and midday on 8 January (Figure 3-26). The most significant rainfall occurred during two distinct periods. 36mm was recorded between 0030 and 0300 on the 7 January and 138.6mm between 0930 on the 7 January and 0100 on the 8 January. The first of these (early on the 7 January), and the period 1900-2200 were particularly intense. Further rainfall occurred in the afternoon and evening of the 8 January.

Figure 3-26: Rainfall Depth at Honister - 15 minute intervals from 0000 7 January 2005



The rarity of the rainfall is shown in Table 3-9. This shows that over the whole period, the total recorded rainfall of 213mm was equivalent to a 1 in 91 year return period (1.1%). The continuous rainfall in the 16 hour period 0900 7 January to 0100 8 January was equivalent to a 1 in 51 year return period (1.96%). Taken individually, peak rainfalls were less rare, typically less than or equal to a one in 10 year event (10%), and less than the 1 in 5 year event (20%) for the maximum intensity of 20mm/hr. This demonstrates the significance of the event's extended duration. FEH screen dumps (Figure 5.3a-d) are included in Appendix 1.

Table 3-9: Rainfall Rarity - Honister

No.	Period	Duration (hrs)	Rainfall (mm)	Return Period* (Years)
1	Jan 7th 0000 – Jan 8th 1200	36	213	91
2	Jan 7th 0915 - Jan 8th 0100	15.75	136	51
3	Jan 7th 1900 - 2200	3	43.8	10
4	Jan 7th 0030 - 0245	2.25	36.2	8.2
5	Jan 7th 0045 - 0145	1	20.2	4.3

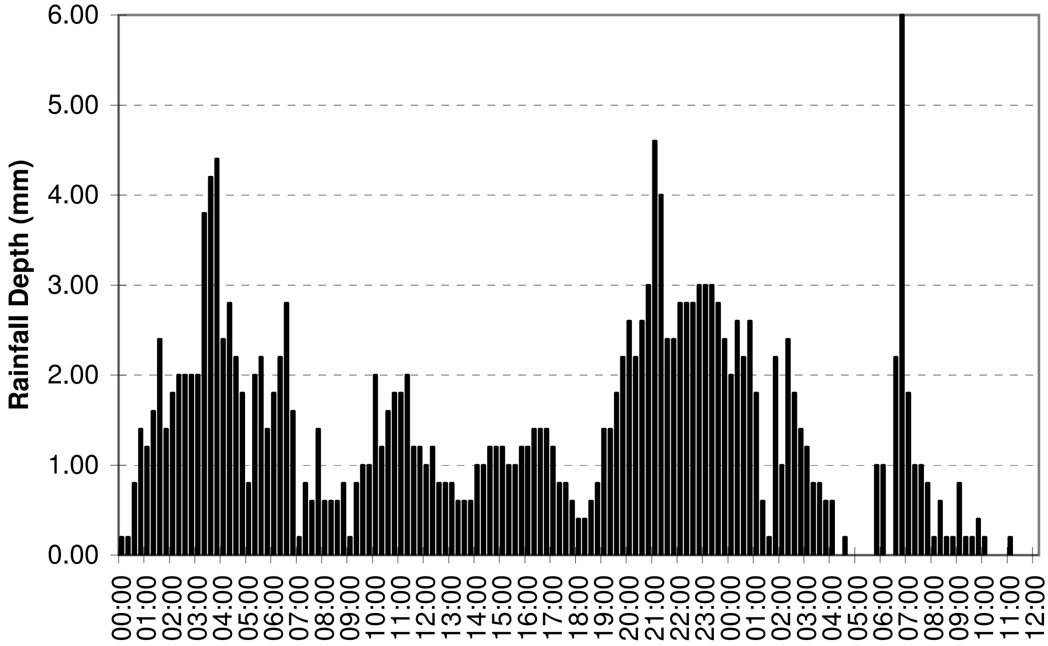
**Source FEH estimate based on point rainfall, annual maxima, sliding scale*

Wet Sleddale

Rainfall at Wet Sleddale followed a similar pattern see Figure 3-27, with 206.8mm recorded over the period, and peaks recorded at 0145 and 2100 on the 7 January.

Individual peaks were discernable at 0300 and 2100 on the 7 January and 0700 on the 8 January.

Figure 3-27: Rainfall Depth at Wet Sleddale - 15 minute intervals from 0000 7 January 2005.



The rarity of the rainfall is shown in Table 3-10. This indicates that 207mm rainfall recorded over the total duration of the event was equivalent to a 173 year return period event (0.58%). The 65mm rainfall measured over six hours on the evening of 7 January was equivalent to 22 year return period (4.5%). Rainfall of shorter duration was generally less significant in terms of rarity, and the peak intensity of 24mm/hr (6mm in 15 minutes) is less than the 1 in 5 year return period (20%). The FEH screen dumps (Figures 5.4a-c) are included in Appendix 1.

Table 3-10: Rainfall Rarity - Wet Sleddale

No.	Period	Duration (hrs)	Rainfall (mm)	Return Period* (Years)
1	Jan 7 0000 – Jan 8 1200	36	206.8	173
2	Jan 7 1900 - Jan 8 0100	6	64.4	21.7
3	Jan 7 0315 - 0415	1	17.6	3.4
4	Jan 7 2015 - 2115	1	43.8	1.8

**Source FEH estimate based on point rainfall, annual maxima, sliding scale*

3.5.2 Summary

- The rarity of the event is associated with its length, rather than the instantaneous intensity of the rainfall.
- Analysis of previous extreme orographic rainfall events indicates a return period of 50 - 100 years (2% - 1%) for an event of this type.
- Analysis of the rainfall records at Honister and Wet Sleddale suggest slightly higher return periods (91 and 173 years (1.1% and 0.58%), respectively) for these particular locations.
- Taken together, the evidence indicates an overall return period of about 100 years (1%).

3.6 <u>Conclusions</u>

- The ground was generally near field capacity prior to the event, due to previous rainfall in December.
- The rainfall event that generated the Cumbria floods was caused by a strong airflow of unusually warm, moist tropical air, forced northwards ahead of an Atlantic cold front, over a period of nearly three days. At the end of this period, the rainfall was enhanced by strong frontal uplift and convection, as a depression centre passed nearby to the north of the area.
- Research suggests that the shape of the vertical wind profile may have contributed to the orographic enhancement.
- The model forecasts captured the event well, in general, but details of the frontal position and timing remained uncertain until about 24 hours before the event. Model rainfall accumulations were substantial, but significantly lower than observed. Daily weather forecasts followed the model guidance.
- The heavy rainfall warning issued at 1529 on 6 January provided excellent guidance.
- The rarity of the event is associated with its length, rather than the instantaneous intensity of the rainfall.
- Taken together, the evidence indicates an overall return period of about 100 years (1%).

3.7 References

Alpert, P., Shafir, H., 1989. A physical model to complement rainfall normals over complex terrain. *J. of Hydrol.*, **110**, 51–62.

Bell, V.A. and Moore, R.J., 2004. A flow routing and flood inundation facility for Nimrod/CMetS. Unpublished contract report available from CEH, Wallingford.

[1] Bowler, N. E., Pierce, C. E., Seed, A., 2004. A probabilistic precipitation forecasting scheme which merges an extrapolation nowcast with a downscaled NWP forecast. Forecasting Research Technical Report No. 433, Met Office, UK, 44pp.

[2] Bowler, N. E., Pierce, C. E., Seed, A., 2004. Development of a precipitation nowcasting algorithm based upon optical flow techniques. *J. of Hydrol.*, **288**, 74–91.

Browning, K. A., 1980. Structure, mechanism and prediction of orographically enhanced rain in Britain. In: R. Hide and P. W. White (Editors), Orographic effects in planetary flows. *Global Atmos. Res. Proj. Publ. Ser*. **23**, 85–114.

Clark, P.A., Browning, K.A. Wang, C., 2005. The sting at the end of the tail: model diagnostics of fine-scale three-dimensional structure of the cloud head. Quarterly Journal of the Royal Meteorological Society,VOL. 131 NO. 610, 2005, pp.2263-2292 1)954117

Hand, W. H., 2002. The Met Office convection diagnosis scheme. *Meteorol. Appl.*, **9(1)**, 69–83.

Harrison, D. L., Driscoll, S. J., Kitchen, M., 2000. Improving precipitation estimates from weather radar using quality control and correction techniques. *Meteorol. Appl.* **6**, 135-144 (2000)

May, B., Cooper, A., Pierce, C., Smith, R., 2005. Post-Event Evaluation, Case Study Report No. 7, Flooding in Carlisle on 7/8 January 2005, A study of Met Office systems. Met Office internal report (available on request from the authors).

Robichaud, A. J., Austin, G. L.,1988. On the modelling of warm orographic rain by the seeder-feeder mechanism. *Quart. J. R. Met. Soc.*, **114**, 967–988.

Smith, R.N.B., Blyth, E.M., Finch, J.W., Goodchild, S., Hall, R.L. and Madry, S., 2004. Soil state and surface hydrology diagnosis based on MOSES in the Met Office Nimrod nowcasting system. Forecasting Research Technical Report No. 428 available from http://www.metoffice.gov.uk/research/nwp/publications/papers/technical_reports/fr.html

4 HYDROLOGY

4.1 Introduction

This section covers the hydrological issues and attributes return periods to the rainfall and flow at various locations. It also examines the performance of the hydrometric network.

4.2 Background

The Environment Agency maintains an extensive network of stations that record rainfall, river flows and/or levels throughout Cumbria.

The rain gauges are of the following types:

- Storage gauges are manually read usually at 0900hrs every day
- Tipping bucket gauges are automatic and record the time for a small amount, typically 0.2mm, to fall

The locations and types of rain gauges are shown in Figure 4-1 and more detail is provided on Map 1 in Appendix 2.

The river gauging stations record the level of a river, typically at 15 minute intervals. For flow gauging stations, the flow is derived from the observed level by means of a stage-discharge equation or rating. Figure 4-2 shows the location of the key gauging stations and Map 2 in Appendix 2 shows the locations in more detail.

The majority of the gauging stations, and many of the tipping bucket rain gauges, are connected via telemetry to the Environment Agency's offices, and the data is available in 'real-time'.

Despite its severity, the majority of the stations operated correctly during the January event. The flooding or the associated gales prevented a small number from operating, such as the rain gauge at Willowholme, Carlisle.

Figure 4-1: Location and Type of Rain Gauges

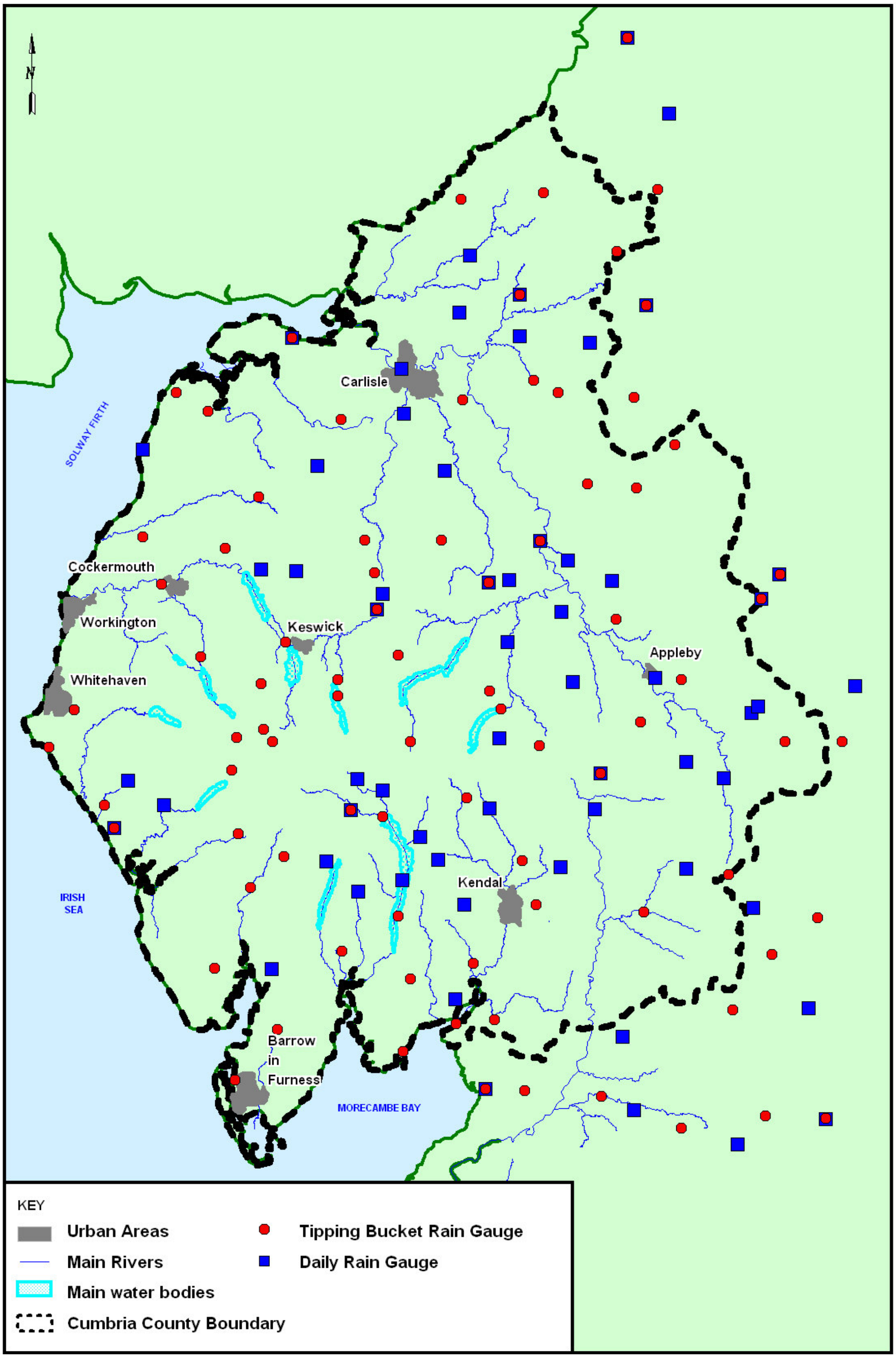
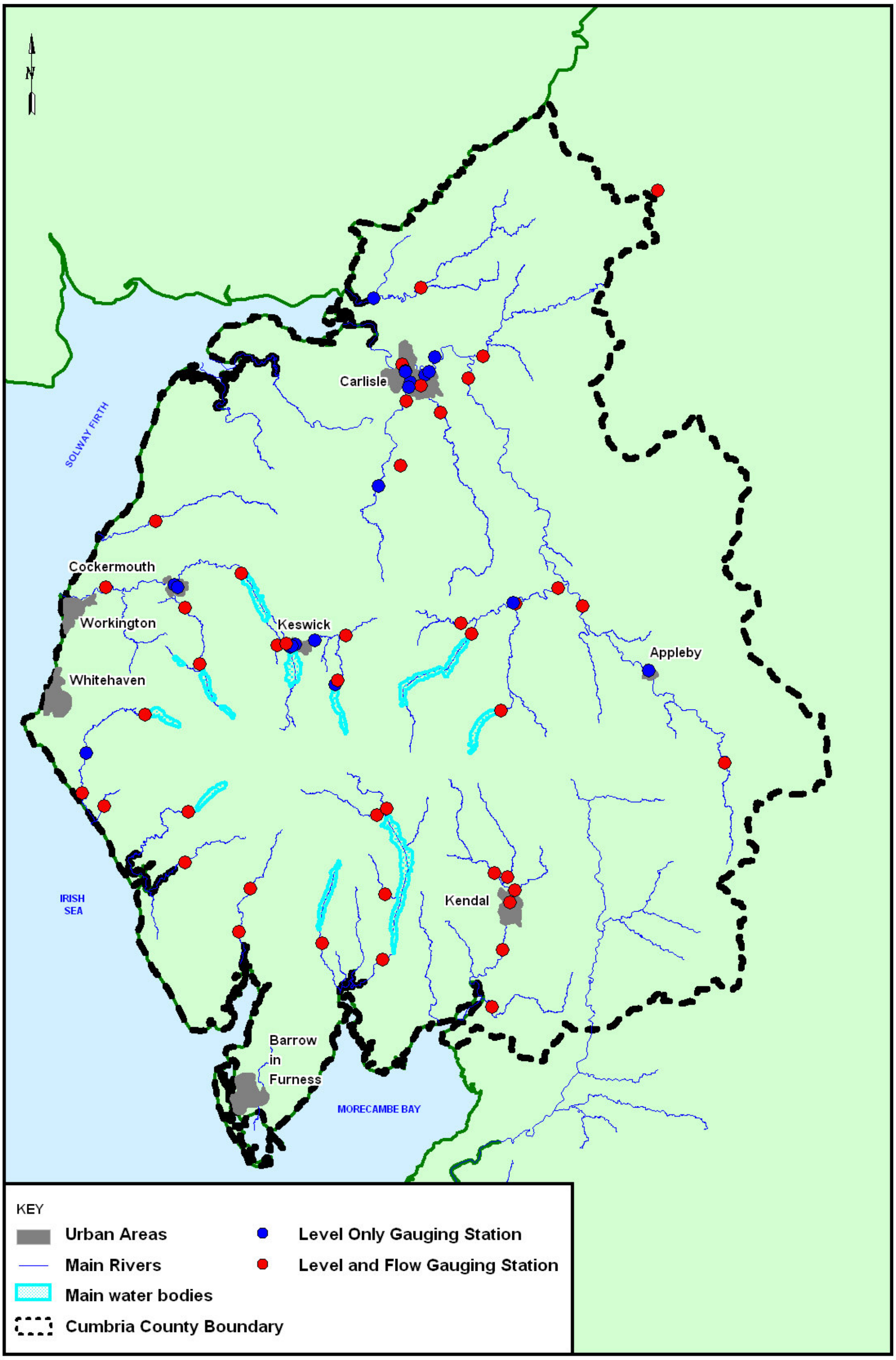


Figure 4-2: Location and Type of Gauging Stations



4.3 Antecedent Conditions

Section 3.2 discusses the antecedent soil conditions in detail. However, the rainfall during the previous days is also important in respect of flows and Table 4-1 shows the rainfall during the five day period prior to the event. The Flood Estimation Handbook suggests the use of a Catchment Wetness Index based on the Soil Moisture Deficit and a portion of the previous five days rainfall. Table 4.1 shows this index for:-

- 0900hrs on 6 January, which is the end of the standard rainfall recording day before the event
- 0000hrs on 7 January, which is approximately the start of the heaviest rainfall

Table 4-1: Antecedent conditions

River	Location	Rainfall (mm) in 5 days up to 0900 6 Jan	Catchment Wetness Index	
			At 0900 6 Jan	At 0000 7 Jan
Eden	Sheepmount GS	31	135	135
Kent	Victoria Bridge GS	43	140	138
Caldew	Confluence with Eden	47	140	139
Greta	Confluence with Derwent	69	149	149
Derwent	Camerton GS	50	142	142
Eden	Appleby	29	135	135

The above figures are not unusual for the Cumbrian catchments.

Another important factor is the state of the lakes and reservoirs at the start of the event. This is discussed in Section 4.6.

4.4 Rainfall

The main period of rainfall began at around midnight on 6 January and continued until the middle of 8 January. Typical totals were 100 to 220mm at the gauges in a band from central Lake District into the Yorkshire Dales. Elsewhere, lower totals were recorded away from the high ground and, for example, only some 20mm was recorded along the coast.

Table 4-2 shows the rainfall amounts for: -

- the two days from 0900hrs on 6 January until 0900hrs on 8 January
- the 36 hours from 0000hrs on 7 January to 1200hrs on 8 January. Only the tipping bucket rain gauges are able to produce totals for this period.

The return periods are calculated using the methodology described in the Flood Estimation Handbook. As anticipated, they vary across the area. The highest return periods of in excess of 1 in 100 years (1%) are generally on high ground in the upper parts of Eden, Eamont and Lune catchments.

Table 4-2: Rainfall amounts between 6 and 8 January 2005

Rain gauge	Catchment	Two days from 0900hrs on 6 Jan 2005		36 hours from 0000hrs on 7 Jan 2005	
		Amount (mm)	Return Period (years)	Amount (mm)	Return Period (years)
Malham Tarn	Aire	75	5		
Kinmount House	Annan (Scotland)	50	<5	45	<5
Ferry House	Brathay, Rothay & Leven	84	<5		
Grange	Brathay, Rothay & Leven	35	<5	35	<5
Grizedale	Brathay, Rothay & Leven	80	<5		
High Newton Reservoir	Brathay, Rothay & Leven	42	<5	41	<5
Oxen Park	Brathay, Rothay & Leven	59	<5	59	<5
Tower Wood S.Wks	Brathay, Rothay & Leven	76	<5		
Brathay Hall	Brathay, Rothay & Leven	120	10	117	10
Elterwater	Brathay, Rothay & Leven	148	10		
Grasmere Tannercroft	Brathay, Rothay & Leven	171	10		
Windermere Black Moss	Brathay, Rothay & Leven	93	10		
Rydal Hall	Brathay, Rothay & Leven	232	175		
Coniston	Duddon & Crake	109	<5		
Grizebeck	Duddon & Crake	28	<5		
Lanthwaite	Duddon & Crake	28	<5	28	<5
Palace Nook	Duddon & Crake	16	<5	16	<5
Seathwaite	Duddon & Crake	102	<5	101	<5
Ulpha Duddon	Duddon & Crake	62	<5	62	<5
Ulverston P.F.	Duddon & Crake	25	<5	25	<5
Walney: South Walney	Duddon & Crake	12	<5		
Boot	Ehen, Calder, Irt & Esk	69	<5	69	<5
Calder Hall	Ehen, Calder, Irt & Esk	47	<5	47	<5
Ennerdale TWks	Ehen, Calder, Irt & Esk	74	<5	72	<5
Peagill	Ehen, Calder, Irt & Esk	52	<5		
Prior Scales Farm	Ehen, Calder, Irt & Esk	55	<5		
Seascale White Heath	Ehen, Calder, Irt & Esk	42	<5		
St Bees	Ehen, Calder, Irt & Esk	30	<5	29	<5
Starling Gill	Ehen, Calder, Irt & Esk	83	<5	80	<5
Summergrove	Ehen, Calder, Irt & Esk	50	<5	50	<5
Wastwater Hotel	Ehen, Calder, Irt & Esk	107	<5	106	<5
Black Sail Ennerdale	Ehen, Calder, Irt & Esk	192	15	181	10
C.A.D.Longtown	Esk & Irthing	58	<5	53	<5
Castle Carrock	Esk & Irthing	52	<5	54	5
Catlowdy	Esk & Irthing	57	<5	52	<5
Crewe Fell F.H.	Esk & Irthing	0	<5	0	<5
Geltsdale	Esk & Irthing	56	<5	56	<5
Walton	Esk & Irthing	49	<5		
Brampton	Esk & Irthing	52	5		
Wiley Sike Gland	Esk & Irthing	72	10	71	10
Coalburn Whitehill	Esk & Irthing	95	20	93	20
Shankbridge	Esk & Irthing	70	25		
Braidlie	Esk (Scotland)	85	10	78	5
Solwaybank	Esk (Scotland)	75	10	67	5
Arnside	Kent & Bela	39	<5	39	<5
Beetham Hall	Kent & Bela	49	<5	49	<5
Fisher Tarn Reservoir	Kent & Bela	0	<5	0	<5
Levens Bridge End	Kent & Bela	57	<5	56	<5
Meathop	Kent & Bela	49	<5		

Rain gauge	Catchment	Two days from 0900hrs on 6 Jan 2005		36 hours from 0000hrs on 7 Jan 2005	
		Amount (mm)	Return Period (years)	Amount (mm)	Return Period (years)
Kentmere Hallowbank	Kent & Bela	130	10	128	10
Longsleddale	Kent & Bela	135	10		
Watchgate	Kent & Bela	106	25	103	20
Cornhow	Lower Derwent & Cocker	94	<5	90	<5
Cockermouth SWKS	Lower Derwent & Cocker	69	10	65	5
Honister	Lower Derwent & Cocker	219	100	204	70
Cumwhinton	Lower Eden	48	<5	49	5
Fordsyke Farm	Lower Eden	56	10		
Drumburgh	Lower Eden	65	25		
Carnforth Crag Bank	Lower Lune	30	<5		
Pedder Potts No 2	Lower Lune	48	<5	48	<5
Wennington Clint	Lower Lune	69	5	69	5
Leck Hall	Lower Lune	82	10		
Bentham Summerhill	Lower Lune	81	15		
Clapham Turnerford	Lower Lune	96	25	95	20
Brothers Water	Lowther & Eamont	175	10	167	10
Green Close Farm	Lowther & Eamont	87	10	84	10
Newton Rigg	Lowther & Eamont	73	20		
High Row	Lowther & Eamont	135	30	128	25
Penrith	Lowther & Eamont	86	60		
Swindale Head Farm	Lowther & Eamont	183	60		
Burnbanks	Lowther & Eamont	176	80	166	60
Moorahall Farm	Lowther & Eamont	150	80	145	60
Penrith Cemetery	Lowther & Eamont	89	80		
Askham Hall	Lowther & Eamont	114	125		
Wet Sleddale	Lowther & Eamont	206	150	198	150
Haresceugh Castle	Middle Eden	58	5	60	5
Kirkby Thore	Middle Eden	52	5	53	5
Langwathby	Middle Eden	56	10		
Riggside Blencarn	Middle Eden	64	15		
Nunwick Hall	Middle Eden	73	30		
Oasis Penrith	Middle Eden	72	40	71	30
Kielder Ridge End	North Tyne	104	30	82	10
Kielder Dam	North Tyne	104	50		
Blackhall Wood	Petteril & Caldew	55	5		
Caldbeck Hall	Petteril & Caldew	103	15	100	15
Mosedale	Petteril & Caldew	128	20	123	20
Broadfield House	Petteril & Caldew	69	25		
Skelton	Petteril & Caldew	114	175	110	150
Tindale	South Tyne	77	15		
Haltwhistle	South Tyne	86	30	62	5
Alston Sewage Works	South Tyne	106	40	110	40
Cow Green	Tees	65	<5		
Old Spital Farm	Tees	38	<5	38	<5
Balderhead Embankment	Tees	81	10		
Greenhills Farm	Tees	107	15		
Knarsdale	Tyne	105	15	105	20
Hartside	Tyne	105	30	105	30
Seathwaite Farm	Upper Derwent & Greta	193	<5	184	<5
Sunderland WWTW	Upper Derwent & Greta	51	<5	48	<5

Rain gauge	Catchment	Two days from 0900hrs on 6 Jan 2005		36 hours from 0000hrs on 7 Jan 2005	
		Amount (mm)	Return Period (years)	Amount (mm)	Return Period (years)
Bassenthwaite	Upper Derwent & Greta	87	15		
Dale Head	Upper Derwent & Greta	162	20	152	15
Mungrisdale	Upper Derwent & Greta	133	20		
High Snab Farm	Upper Derwent & Greta	180	40	171	30
Mungrisdale Low Beckside	Upper Derwent & Greta	148	50		
St John's Beck	Upper Derwent & Greta	178	80	167	60
Barras	Upper Eden	59	<5	58	<5
Brough	Upper Eden	71	5		
North Stainmore	Upper Eden	73	5		
Brackenber	Upper Eden	73	10	74	15
Aisgill	Upper Eden	141	15	136	10
Appleby Mill Hill	Upper Eden	79	30		
Kirkby Stephen	Upper Eden	122	40		
Sleagill	Upper Eden	110	80		
Scale Beck	Upper Eden	129	125	125	100
Crosby Garrett	Upper Eden	140	175		
Tebay	Upper Lune	124	15		
Ravenstonedale	Upper Lune	146	20		
Sedburgh	Upper Lune	123	30	119	25
Orton Shallowford	Upper Lune	170	150		
Stainforth	Upper Ribble & Hodder	68	5	68	5
Far Gearstones	Upper Ribble & Hodder	116	15	113	10
Giggleswick Beverley	Upper Ribble & Hodder	80	20		
Sedbusk	Ure	102	15	102	15
Moorland Cottage	Ure	159	70		
Tow Hill	Ure	168	70	165	60
Dearham	Wampool & Ellen	53	<5	51	<5
Abbeytown Kingside	Wampool & Ellen	54	5	52	<5
Mawbray	Wampool & Ellen	59	5		
Silloth	Wampool & Ellen	55	5	52	5
Thursby WWTW	Wampool & Ellen	58	10	58	10
Westward Park Farm	Wampool & Ellen	76	15		
Quarry Hill Farm	Wampool & Ellen	86	20	82	15
Beckermonds	Wharfe	121	25	121	25

Data from all relevant rain gauges is included in Appendix 3.

Table 4-3 shows the catchment average rainfall totals over selected catchments for the same periods in Table 4-2. It was derived from the relevant gauges using a Thiessen polygons method of weighting the individual gauge totals. As expected, the catchment average rainfall return periods are lower than those for point rainfall. The catchment totals also show more sensitivity to the period considered.

Table 4-3: Catchment Average Rainfall

Catchment			0900hrs 6 January to 0900hrs 8 January (48 hours)		0000hrs 7 January to 1200hrs 8 January (36 hours)	
River	**Downstream Location**	**Area (km^2)**	**Rainfall (mm)**	**Return Period (years)**	**Rainfall (mm)**	**Return Period (years)**
Eden	Sheepmount GS	2239	83	15	81	30
Kent	Victoria Bridge GS	194	116	15	113	25
Caldew	Confluence with Eden	257	100	30	97	50
Greta	Confluence with Derwent	235	164	30	155	40
Derwent	Camerton GS	664	121	20	114	30
Eden	Appleby GS	328	91	10	90	20

The rainfall totals and return periods are plotted on Maps 3 to 6 in Appendix 2 and those for the 48 hours between 0900hrs on 6 January and 0900hrs on 8 January are also shown on Figure 4-3 and Figure 4-4. It is worth noting that the shape of the isohyets on the maps is partly due to the location of the gauges as well as the spatial distribution of the rainfall.

Figure 4-3: Isohyets for the January 2005 Event

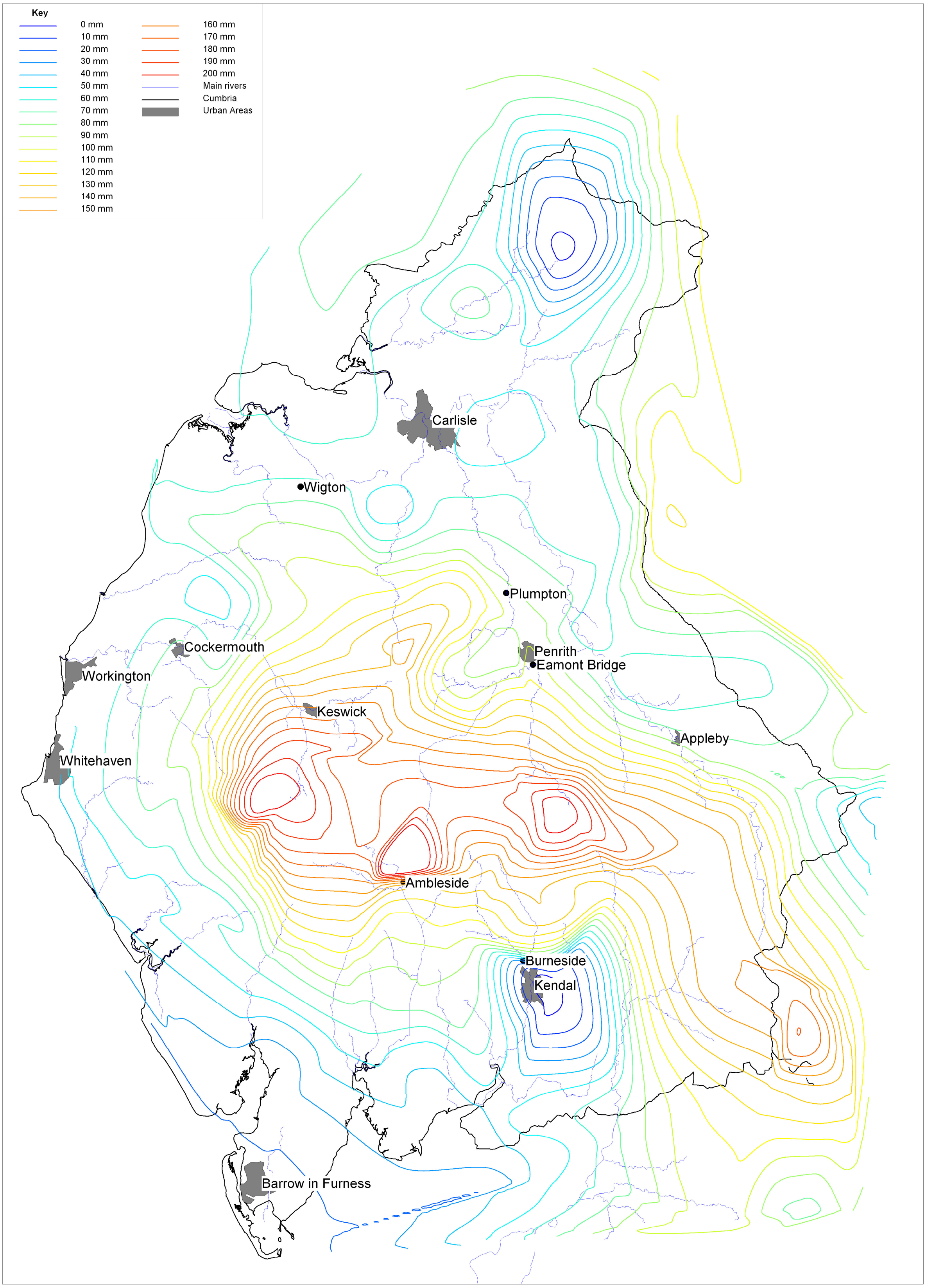


Figure 4-4: Rainfall Return Periods for the January 2005 Event

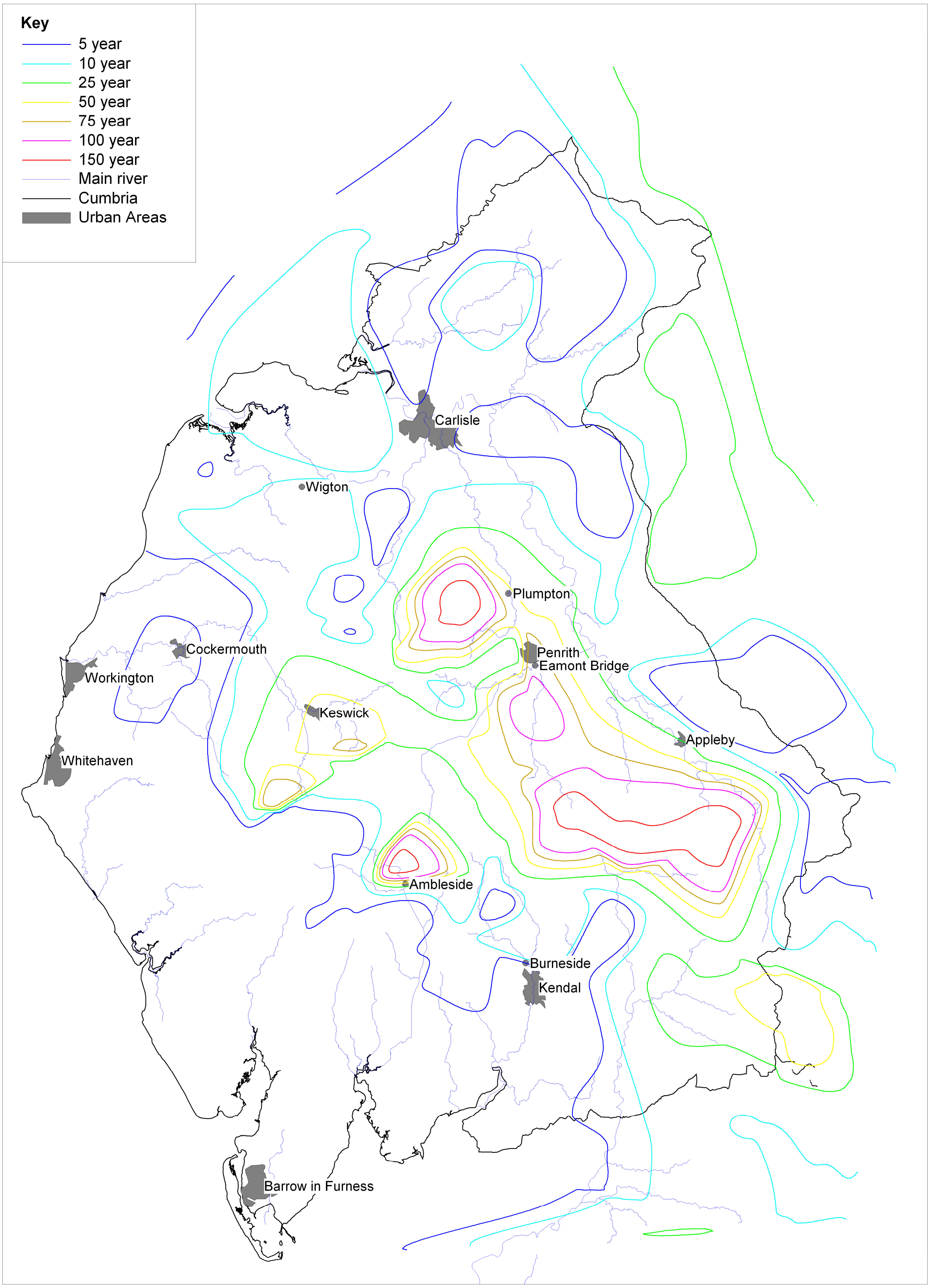


Figure 4-5 to Figure 4-11 show the rainfall hyetographs at key locations.

Figure 4-5: Rainfall Hyetograph at key locations in the Kent Catchment

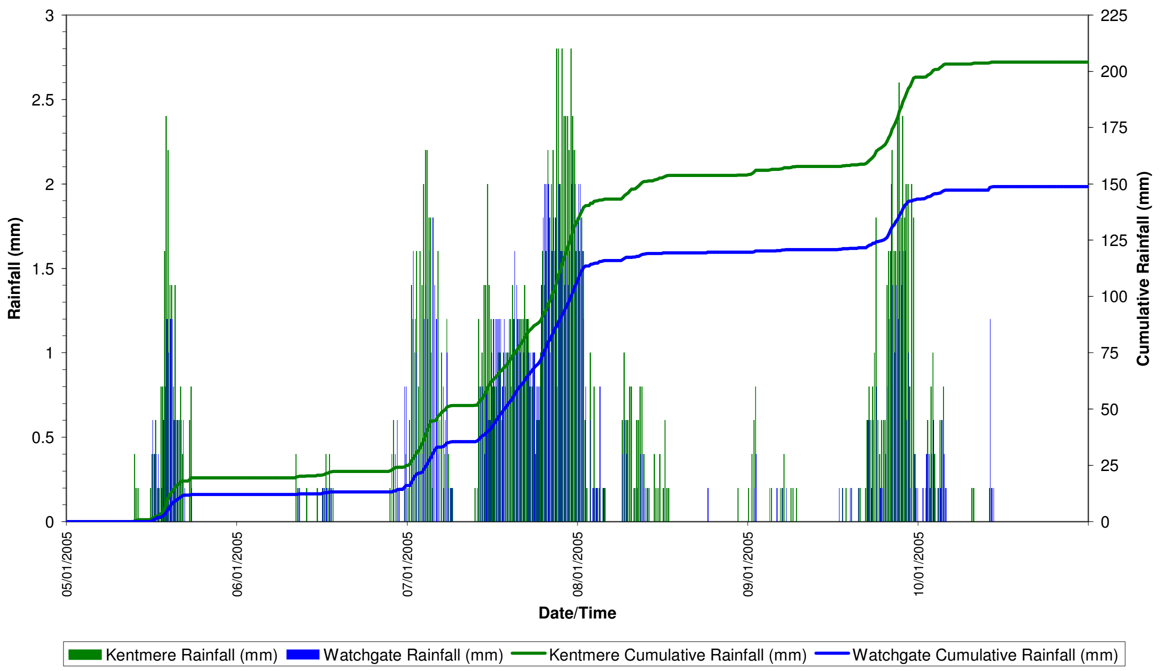


Figure 4-6: Rainfall Hyetograph at key locations in the Derwent and Greta Sub-catchment

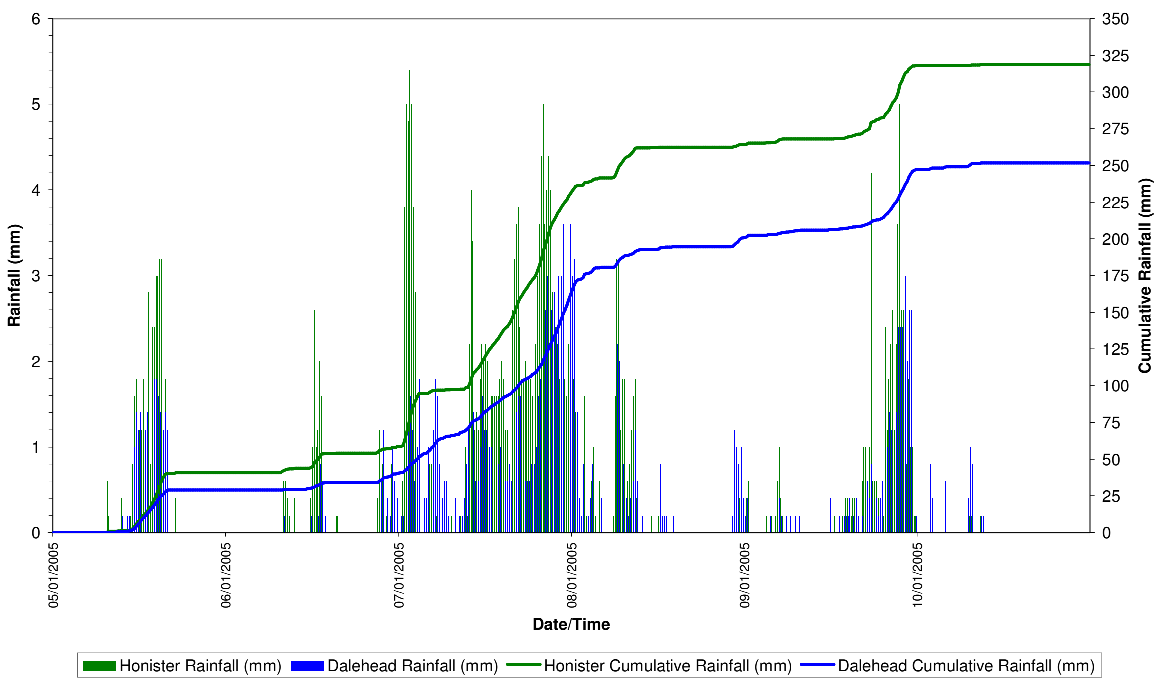


Figure 4-7: Rainfall Hyetograph at key locations in the Cocker Sub-catchment

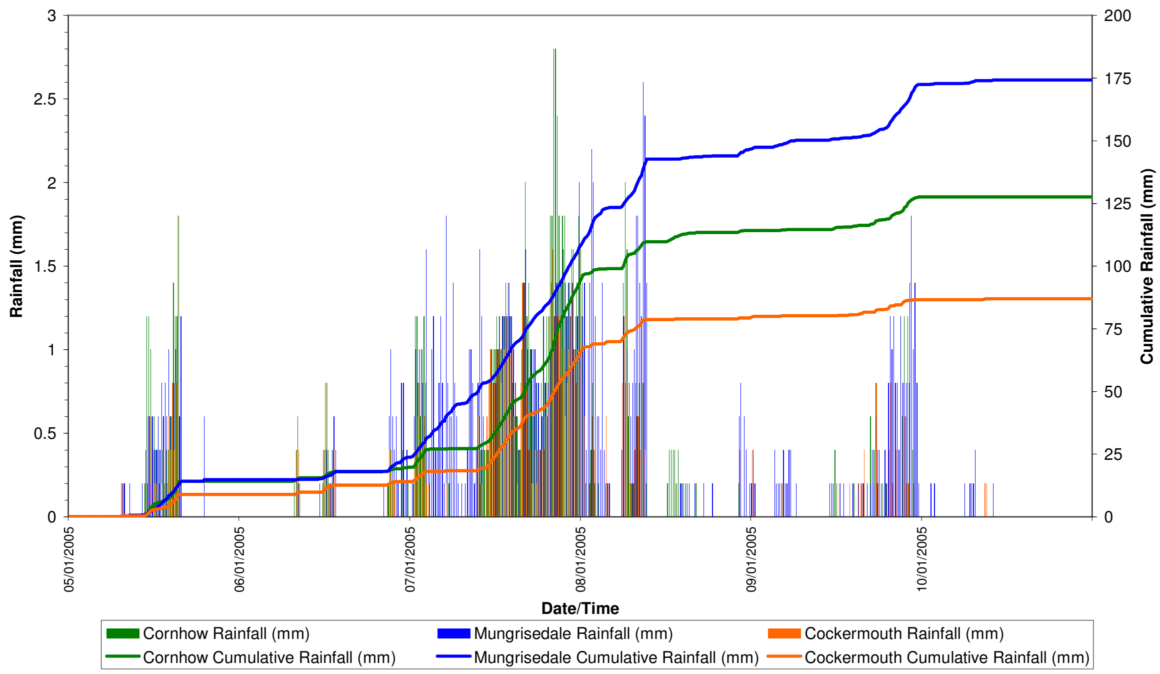


Figure 4-8: Rainfall Hyetograph at key locations in the Petteril and Caldew Sub-catchment

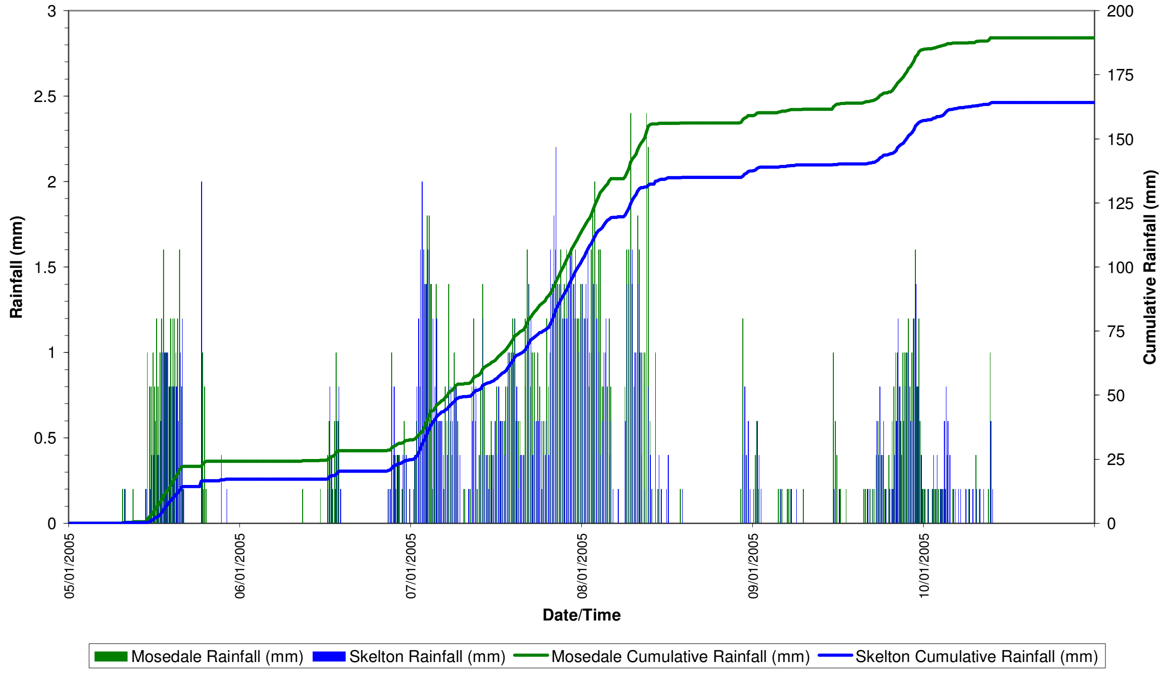


Figure 4-9: Rainfall Hyetograph at key locations in the Eden and Irthing Sub-catchment

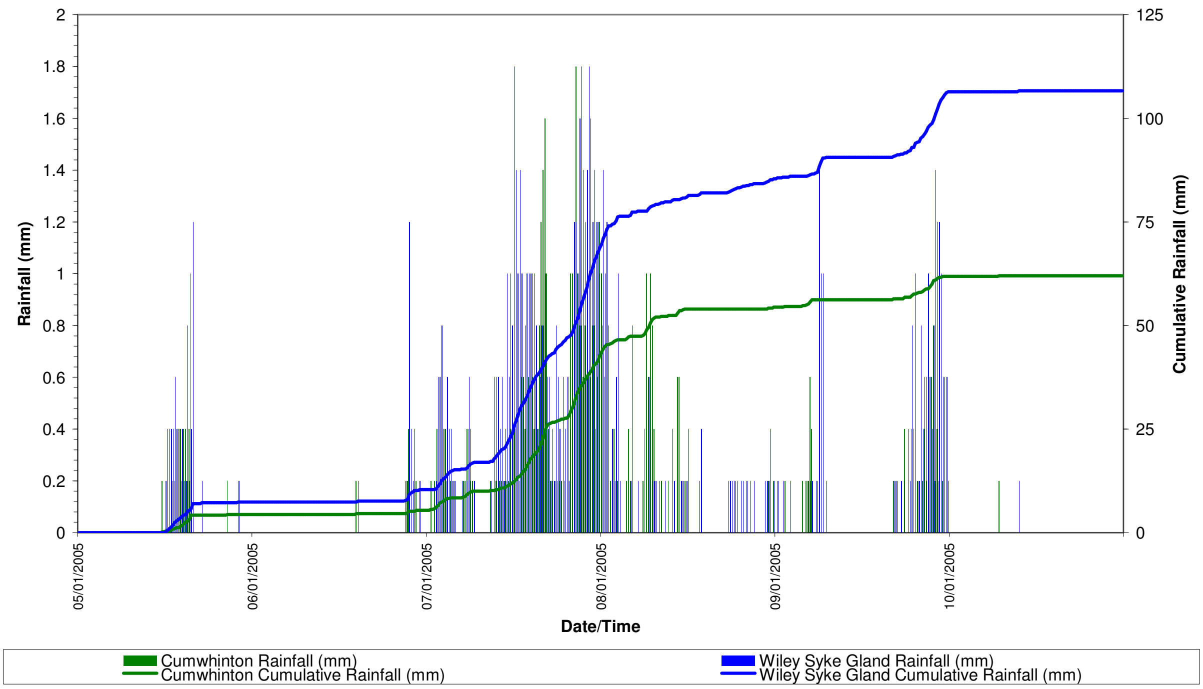


Figure 4-10: Rainfall Hyetograph at key locations in the Eden Catchment

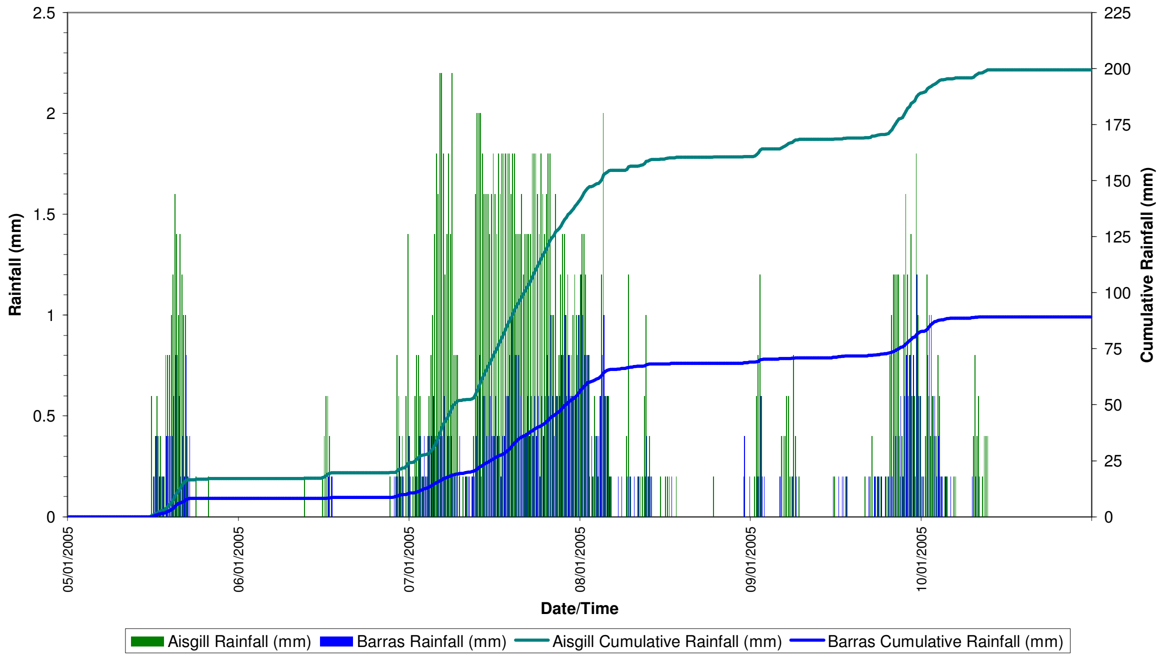
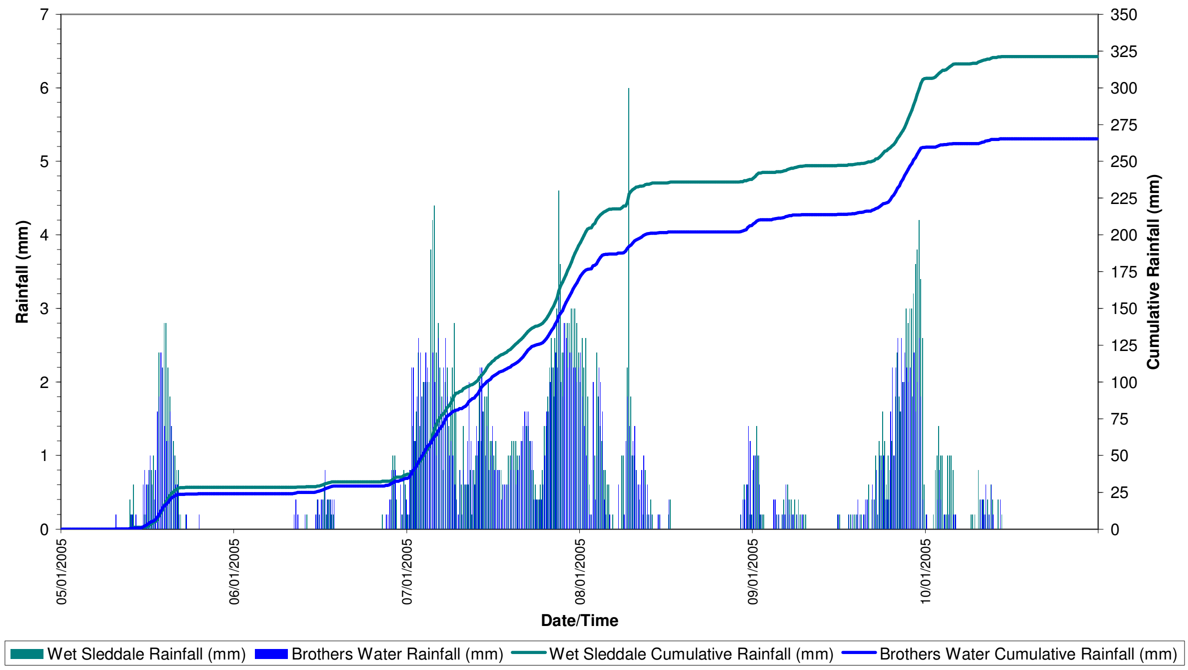


Figure 4-11: Rainfall Hyetograph at key locations in the Eamont Catchment



4.5 Flows

As described previously, the flows at most locations are calculated using a stage discharge equation. At some locations, the 2005 flows were the highest recorded, and the quality of such relationships and, hence, the derived flows are questionable. This is discussed in Section 4.10. Table 4-4 lists those locations where the level recorded in January 2005 was the highest since records began and data from all relevant gauging stations is included in Appendix 3.

Table 4-4: Locations where flows were highest since records began

Location	River	Catchment	Record since
Southwaite Bridge	Cocker	Derwent	1967
Ouse Bridge	Derwent	Derwent	1968
Portinscale	Derwent	Derwent	1972
Low Briery	Greta	Derwent	1971
Thirlmere	St John's Beck	Derwent	1974
Pooley Bridge	Eamont	Eden	1976
Udford	Eamont	Eden	1961
Great Corby	Eden	Eden	1997 (see note)
Great Musgrave Bridge	Eden	Eden	2000
Kirkby Stephen	Eden	Eden	1972
Sheepmount	Eden	Eden	1967
Temple Sowerby	Eden	Eden	1964
Greenholme	Irthing	Eden	1967
Harraby Green	Petteril	Eden	1964
Sedgwick	Kent	Kent	1971
Victoria Bridge	Kent	Kent	1968
Mint Bridge	Mint	Kent	1970
Sprint Mill	Sprint	Kent	1970
Jeffy Knotts	Brathay	Leven	1971
Note: Great Corby replaces the gauging station at Warwick Bridge, which was open from 1959 to 1998. The combined record therefore starts in 1959			

Using the statistical methods in the Flood Estimation Handbook, the return period of the peak flow at each gauging station was assessed and compared to those from other studies. The findings are shown in Table 4-5.

The recorded flow of 1520 m^3/s at the Sheepmount Gauging Station in Carlisle is the highest recorded in the catchment. It is believed to be the highest recorded in the Environment Agency's archive of river flows in England and Wales, and has a return period of in excess of 175 years (0.57%).

Elsewhere in the catchment, flows in the River Greta in Keswick and the River Kent in Kendal had return periods of between 50 and 100 years.

The return periods in Table 4-5 are the best estimates available at this time. In future, these estimates may be revised due to a better understanding of the flow recorded at a particular location or the availability of data from subsequent floods. Comparison of return periods in Table 4-5 with the return periods of the rainfall in Table 4-2 and Table 4-3 shows some significant variation. This demonstrates the impact of the runoff mechanism on the timing and amount of water that reaches the river system. It is also influenced by other factors, such as uncertainty in the methods of assessing return periods, the location of rain gauges relative to the actual rain, the accuracy of the measurements and the antecedent conditions.

Figure 4-12 to Figure 4-15 show the flow hydrographs at key locations.

Table 4-5: Peak Flows in January 2005

Gauging Station	CEH_Ref	Watercourse	Catchment	Period of Record (years)	Recorded Flow (m^3/s)	Highest on Record	Return Period (years)	Comments
Beetham	73008	Bela	Bela	36	62	No	20	
Calder Hall	74006	Calder	Calder	32	40	No	<5	
Low Nibthwaite	73002	Crake	Crake	42	19	No	<5	
Camerton	75002	Derwent	Derwent	45	294	Yes	50	
Low Briery	75009	Greta	Derwent	34	270	Yes	75	
Ouse Bridge	75003	Derwent	Derwent	38	146	Yes	75	Return period from River Derwent Model – Cockermouth Update report (Nov 2005)
Portinscale	75005	Derwent	Derwent	33	158	Yes	25	
Southwaite Bridge	75004	Cocker	Derwent	39	87	Yes	28	Return period from: River Derwent Model – Cockermouth Update report (Nov 2005)
Thirlmere	75001	St John's Beck	Derwent	31	103	Yes	50	
Threlkeld	75007	Glendermackin	Derwent	31	80	No	20	
Duddon Hall	74001	Duddon	Duddon					The January 2005 flood was not highest flow of the year
Ulpha	74008	Duddon	Duddon	32	65	Yes	<5	
Burnbanks	76001	Haweswater Beck	Eden	27	28	No	10	
Coal Burn	76011	Coal Burn	Eden	30	3	No	10	
Cummersdale	76809	Caldew	Eden	8	253	Yes	75	Caldew peak flow revised to 253m^3/s by calculations after the event
Dacre Bridge	76811	Dacre Beck	Eden	8	49	No	20	
Eamont Bridge	76004	Lowther	Eden	43	198	Yes	35	
Appleby	-	Eden	Eden	21	n/a	Yes	50-100	Level only site. Return period based on Environment Agency calculations on level record

Gauging Station	CEH_Ref	Watercourse	Catchment	Period of Record (years)	Recorded Flow (m^3/s)	Highest on Record	Return Period (years)	Comments
Great Corby	76810	Eden	Eden	46	950	Yes	100	Existing stage discharge relationship gives a peak flow of 854 m^3/s; however post event hydraulic review, using hydraulic modeling, suggests a figure of about 1100 m^3/s. Hence a figure of 950 m^3/s has been used
Great Musgrave Bridge	76806	Eden	Eden	5	277	Yes	25	Stage discharge relationship revised subsequent to the event
Greenholme	76008	Irthing	Eden	38	278	Yes	75	
Harraby Green	76010	Petteril	Eden	35	107	Yes	100	Existing stage discharge relationship gives a peak flow of 83 m^3/s; however post event hydraulic review gives 107 m^3/s.
Kirkby Stephen	76014	Eden	Eden	34	129	Equal	25	
Pooley Bridge	76015	Eamont	Eden	29	108	Yes	50	
Sheepmount	76007	Eden	Eden	39	1520	Yes	175-200	Calculations after the event confirmed that the existing stage discharge relationship was appropriate
Temple Sowerby	76005	Eden	Eden	41	391	Yes	25	Stage discharge relationship under review; therefore peak flow may be adjusted in the future.
Udford	76003	Eamont	Eden	44	295	Yes	50	
Bleach Green Weir	74003	Ehen	Ehen	32	41	No	5	
Braystones FMS	74005	Ehen	Ehen	31	64	No	<5	
Bullgill	75017	Ellen	Ellen	29	50	Yes	25+	
Cropple How	74007	Esk	Esk	31	107	No	5	
Canonbie	77002	Esk (Scotland)	Esk (Scotland)	43	469	No	10	
Galesyke	74002	Irt	Irt	37	22	No	5	
Mint Bridge	73011	Mint	Kent	36	115	Yes	50	

Gauging Station	CEH_Ref	Watercourse	Catchment	Period of Record (years)	Recorded Flow (m^3/s)	Highest on Record	Return Period (years)	Comments
Sedgwick	73005	Kent	Kent	37	350	Yes	100	Existing stage discharge relationship gives a peak flow of 441 m^3/s; however post event hydraulic review suggests 350 m^3/s.
Sprint Mill	73009	Sprint	Kent	36	83	Yes	60	
Victoria Bridge	73012	Kent	Kent	32	300	Yes	100	Peak flow of 300 m^3/s suggested based on i) ADCP readings during high flows indicating under estimate and ii) review of flows from upstream stations. From existing stage discharge relationship, flow is 240 m^3/s
Eel House Bridge	73006	Cunsey Beck	Leven	32	9	No	<5	
Jeffy Knotts	73014	Brathay	Leven	35	79	Yes	40	
Newby Bridge FMS	73010	Leven	Leven	61	110	No	20	
Brigflatts	72011	Rawthey	Lune	37	502	N	25	
Caton	72004	Lune	Lune	37	1020	No	25	
Galgate	72014	Conder	Lune					The January 2005 flood was not highest flow of the year
High Keer Weir	73015	Keer	Lune	35	25	No	20	
Killington	72005	Lune	Lune	34	801	Yes	100	
Lune Bridge	72015	Lune	Lune	26	465	Yes	25	
Wennington	72009	Wenning	Lune	34	208	No	15	
Wray	72003	Hindburn	Lune	38	314	No	15	

Figure 4-12: Flow Hydrographs at key locations in the Kent Catchment

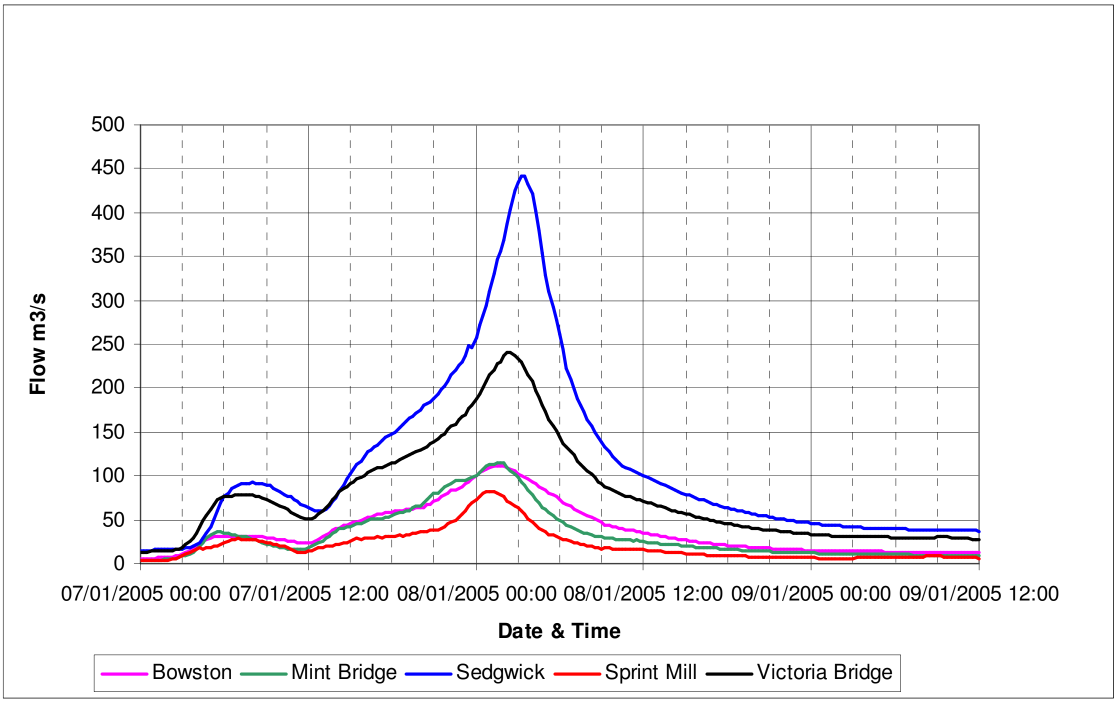


Figure 4-13: Flow Hydrographs at key locations in the Derwent Catchment

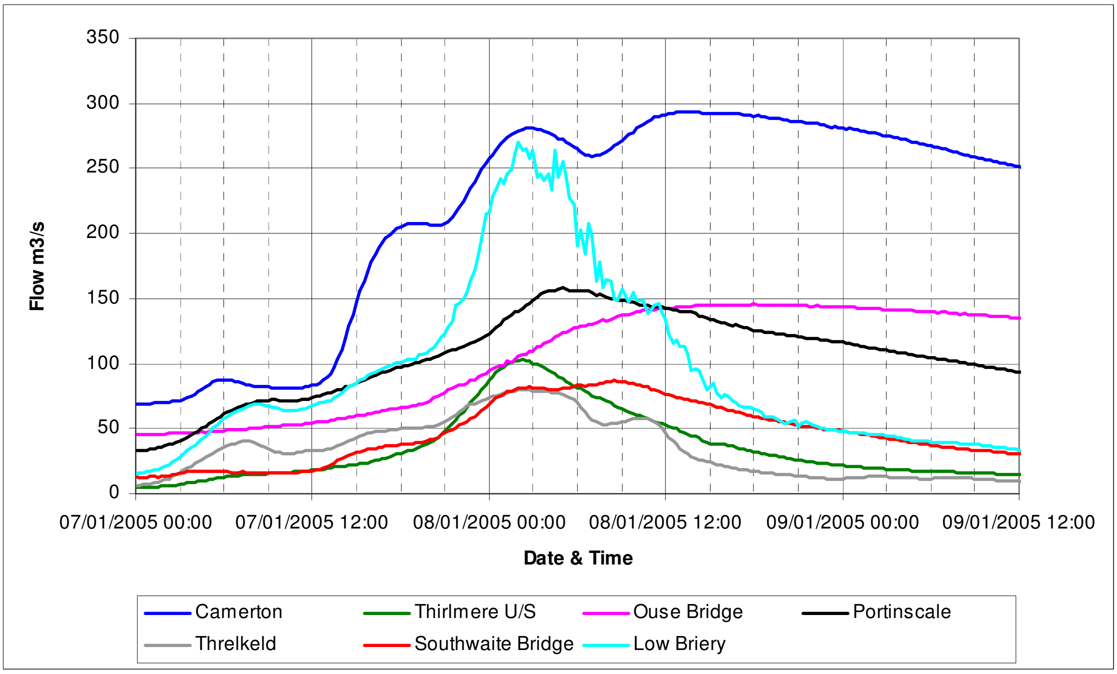


Figure 4-14: Flow Hydrograph at key locations in the Lower Eden Catchment

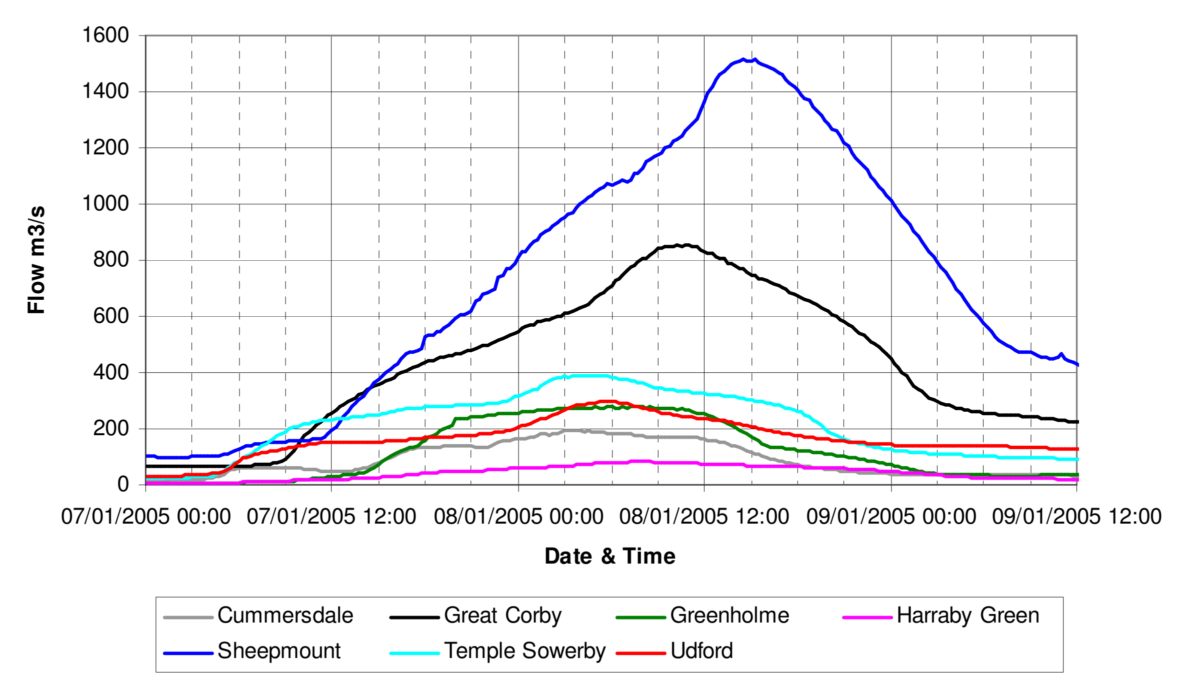
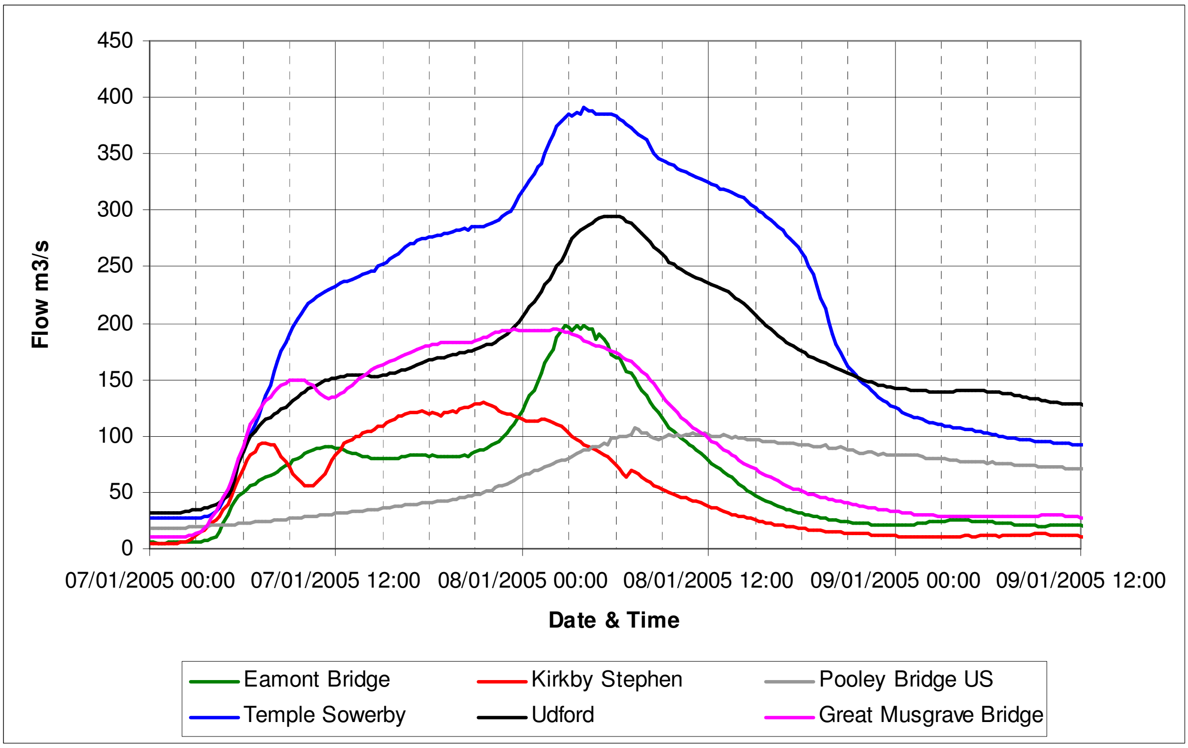


Figure 4-15: Flow Hydrograph at key locations in the Upper Eden Catchment



4.6 Lakes and Reservoirs

There are a large number of lakes and reservoirs in Cumbria. The larger reservoirs were developed to supply water to Manchester and other parts of north west England. The degree of attenuation depends on how full they are at the start of the event and Table 4-6 shows the condition of some of them during the event.

Table 4-6: Condition of lakes and reservoirs

Lake (recording location)	Key Downstream Settlements	Level prior to event (2100hrs 6 Jan) (see Note 1)	Condition during event
Ullswater (Glenridding Pier)	Eamont Bridge Carlisle	1.142m (1.08m)	• 2.538m • **Maximum level on record** • Records since 1961, but 1975-86 missing • (2.09m)
Haweswater Reservoir	Carlisle	29.12m Spill level = 31.39m (~30.2m)	• 31.84m • 3rd maximum on record (Records began Apr 1997) (Max was 31.93m 1 Feb 2002 • Spill began ~2000hrs 7 Jan
Wet Sleddale Reservoir	Carlisle	16.92m Spill not known Full & spilling	• 19.22m • Increased spill from ~0100hrs 7 Jan
Thirlmere Reservoir	Keswick Cockermouth	16.722 m Spill = 16.55m Full & spilling (~16.55)	• 17.432m • **Maximum level on record** (Records began Nov 1997) • Increased in spill from ~ 0100hrs 7 Jan
Derwent Water (Lodore)	Keswick Cockermouth	1.563m	• 3.364m • **Maximum level on record** (Records began Jul 1995)
Bassenthwaite Lake (Castle How)	Cockermouth	1.858m (~1.65m)	• 3.708m • **Maximum level on record** (Records began Jun 1999) • Previously measured at Peil Wyke, and levels are comparable with Castle How. (Peil Wyke levels began July 1970) • Jan 1995 level = 3.19 m at Peil Wyke
Crummock Water	Cockermouth	1.745m Spill level = 1.55m (1.69m)	• 2.542m • **Maximum level on record** (Records since 1976, but 1978-81 missing and step in record ~1992) • Jan 1995 level = 2.272m

Note 1: Values in brackets are from the January 1995 event

4.6.1 Thirlmere

Thirlmere is located some 6km south of Keswick and United Utilities operate it to supply water to Manchester. The overflow from the reservoir is St John's Beck, which is a tributary of the River Greta.

The water level in the reservoir was at the top of the spillway on 23 December 2004 and from that point onwards the reservoir was full and overflowing. Water overflowed until after the flooding in Keswick and other locations.

During the flood event, there were two peaks in the flow in the River Greta at Keswick. The first was at 0200hrs on 8 January and the second was at 0430hrs on the same day. Both reached a similar level. The peak flow from Thirlmere was at 0300hrs and this would have contributed to the second peak. However, the second peak was similar to the first and the effect of flow from Thirlmere was not significant.

Indeed, it should be borne in mind that the reservoir would have attenuated peak flows through it, even though it was full and overflowing. This helps explain the shape of the hydrograph in Keswick with the two peaks.

4.6.2 Haweswater

Haweswater Reservoir is located about 15km south of Penrith; it is also owned and operated by United Utilities to supply water to Manchester. The overflow discharges to Haweswater Beck, which in turn flows in the River Lowther, a tributary of the River Eamont. The Eamont flows into the River Eden near Edenhall, Penrith.

The level in Haweswater Reservoir reached the spillway at 1000hrs on 8 January. However, the peak flow downstream in the River Lowther occurred earlier that day, at 0300hrs.

In conclusion, during the January 2005 flood, Haweswater provided flood storage and, hence, reduced the downstream flood volumes and flows.

4.7 Time of travel

Table 4-7 compares the time of flood peaks at a number of locations. Where these are on the same river, this is an indication of the time of travel of the ‘flood wave’. In some cases, the times have been compared to show the relative timing in adjacent rivers.

Table 4-7: Comparison of time of flood peaks

Downstream Station			Upstream Station			
Station Name	*Watercourse*	*Time of Peak*	*Station Name*	*Watercourse*	*Time of Peak*	*Time Difference (hrs)*
KENT, SPRINT & MINT						
Sedgwick	**Kent**	08/01/2005 03:15	**Victoria Bridge**	**Kent**	08/01/2005 02:15	1.00
			Mint Bridge	**Mint**	08/01/2005 01:45	1.50
			Sprint Mill	**Sprint**	08/01/2005 01:00	2.25
DERWENT						
Camerton	**Derwent**	08/01/2005 13:45	**Ouse Bridge**	**Derwent**	08/01/2005 18:00	-4.25
			Harris Footbridge	**Derwent**	08/01/2005 08:45	5.00
			Portinscale	**Derwent**	08/01/2005 05:00	8.75
			South Street Footbridge	**Cocker**	08/01/2005 09:30	4.25
			Threlkeld	**Glendermackin**	08/01/2005 02:30	11.25
			Low Briery	**Greta**	08/01/2005 02:00	11.75
LOWER EDEN, CALDEW, PETTERIL & IRTHING						
Sheepmount	**Eden**	08/01/2005 14:30	**Denton Holme**	**Caldew**	08/01/2005 04:30	10.00
			Cummersdale	**Caldew**	08/01/2005 03:15	11.25
			Botcherby Bridge	**Petteril**	08/01/2005 14:15	0.25
			Harraby Green	**Petteril**	08/01/2005 07:30	7.00
			Greenholme	**Irthing**	08/01/2005 06:00	8.50
			Great Corby	**Eden**	08/01/2005 10:45	3.75
			Temple Sowerby	**Eden**	08/01/2005 04:00	10.50
			Udford	**Eamont**	08/01/2005 05:45	8.75
UPPER EDEN						
Temple Sowerby	**Eden**	08/01/2005 04:00	**Appleby**	**Eden**	08/01/2005 04:15	-0.25
			Great Musgrave Bridge	**Eden**	07/01/2005 23:30	4.50
			Kirkby Stephen	**Eden**	07/01/2005 21:30	6.50
EAMONT & LOWTHER						
Udford	**Eamont**	08/01/2005 05:45	**Eamont Bridge Farm**	**Eamont**	08/01/2005 04:45	1.00
			Pooley Bridge	**Eamont**	08/01/2005 07:15	-1.50
			Dacre Bridge	**Dacre**	08/01/2005 02:30	3.25
			Eamont Bridge	**Lowther**	08/01/2005 02:45	3.00

The analysis indicates that the floods in the smaller tributaries of the Eden, such as the Caldew, Petteril and Irthing, occur several hours before the peak in Carlisle. It also shows the attenuation effects of large lakes with the peak flow at Pooley Bridge and Ouse Bridge Gauging Stations occurring at a later time.

One anomaly is that the peak at Appleby occurs 15 minutes after that at Temple Sowerby, which is about 10km downstream. However, although the time given in Table 4-7 is the time of the greatest flow recorded, the peaks at these stations are extended over several hours. These "flattened" peaks show small oscillations over periods of 4-5 hours. This makes it more difficult to state a time difference between the peaks at these two stations accurately.

4.8 Volumes – comparison of rainfall and runoff

Table 4-8 compares the volume of rain that fell upstream of the Sheepmount and Camerton Gauging Stations, and the volume of flow through each station. The former were calculated from data from the tipping bucket gauges, which were converted to a catchment basis using a Thiessen polygon method. The latter were calculated by removing a small baseflow component from the total flow volume. Further details of these calculations are included in Appendix 4.

Table 4-8: Comparison of rainfall volume and runoff (flow) volume

Location	**Volume of Rainfall (m^3)**	**Volume of runoff (m^3)**	**% Runoff**
River Eden @ Sheepmount	201,286,000	147,205,000	73%
River Derwent @ Camerton	109,805,000	70,591,000	64%

There is a very high percentage runoff at each station. This is, in part, due to the wet nature of the catchment at the start of the event, which resulted in the majority of the rainfall draining quickly to the watercourses. However, as discussed in Section 4.10, the tipping bucket gauges may under record the rainfall.

Figure 4-16, Figure 4-17 and Figure 4-18 show the catchment rainfall in 15 minute totals versus the flows for the Eden catchment to Sheepmount, the Derwent catchment to Camerton and the Kent catchment to Sedgwick respectively. These show that, although there was some rainfall in the days before the event, the rivers did not react significantly until some hours after the start of the main rainfall at midnight on 7 January. The hydrographs also show the Rivers Eden and Kent reacting to rainfall on 10/11 January.

Figure 4-16: Eden Catchment Runoff

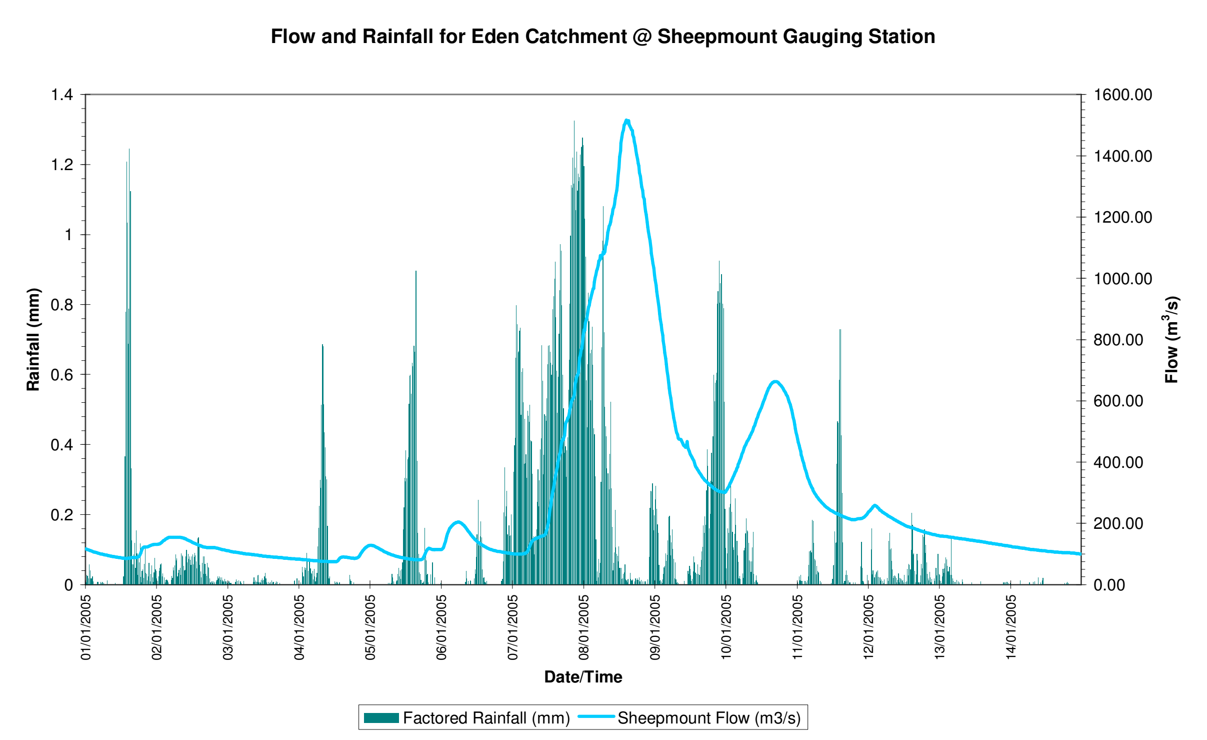


Figure 4-17: Derwent Catchment Runoff

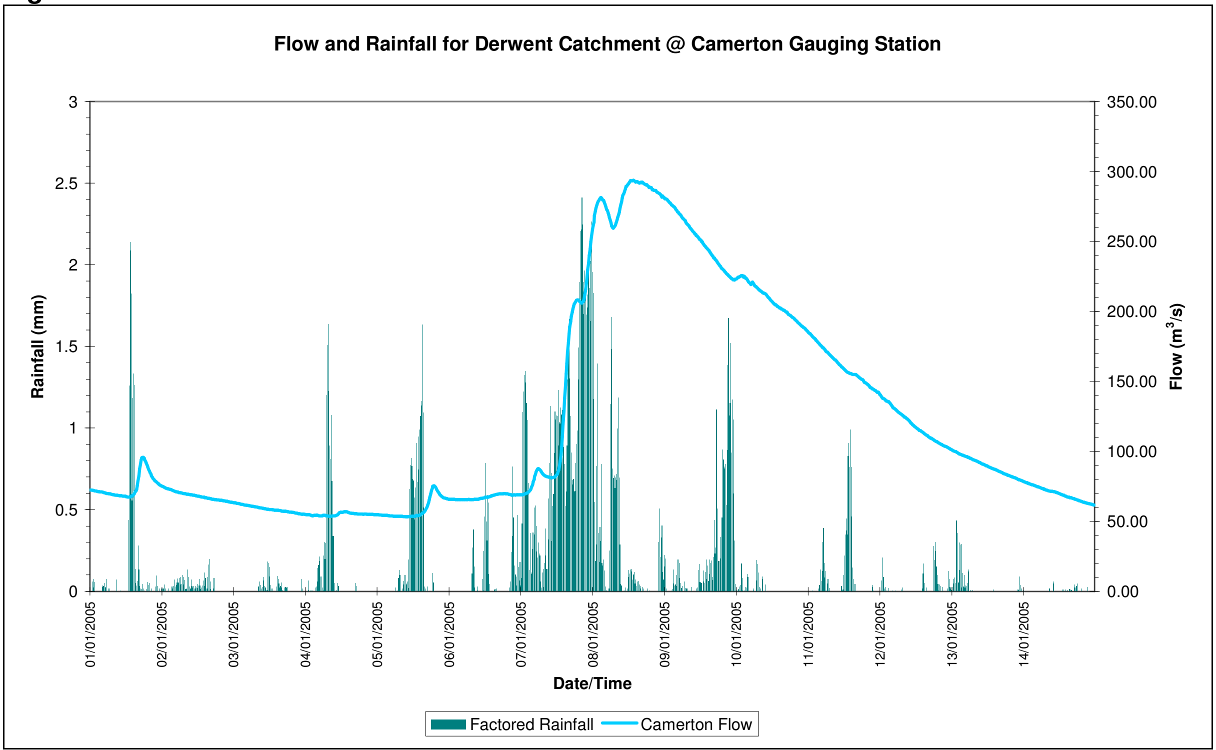
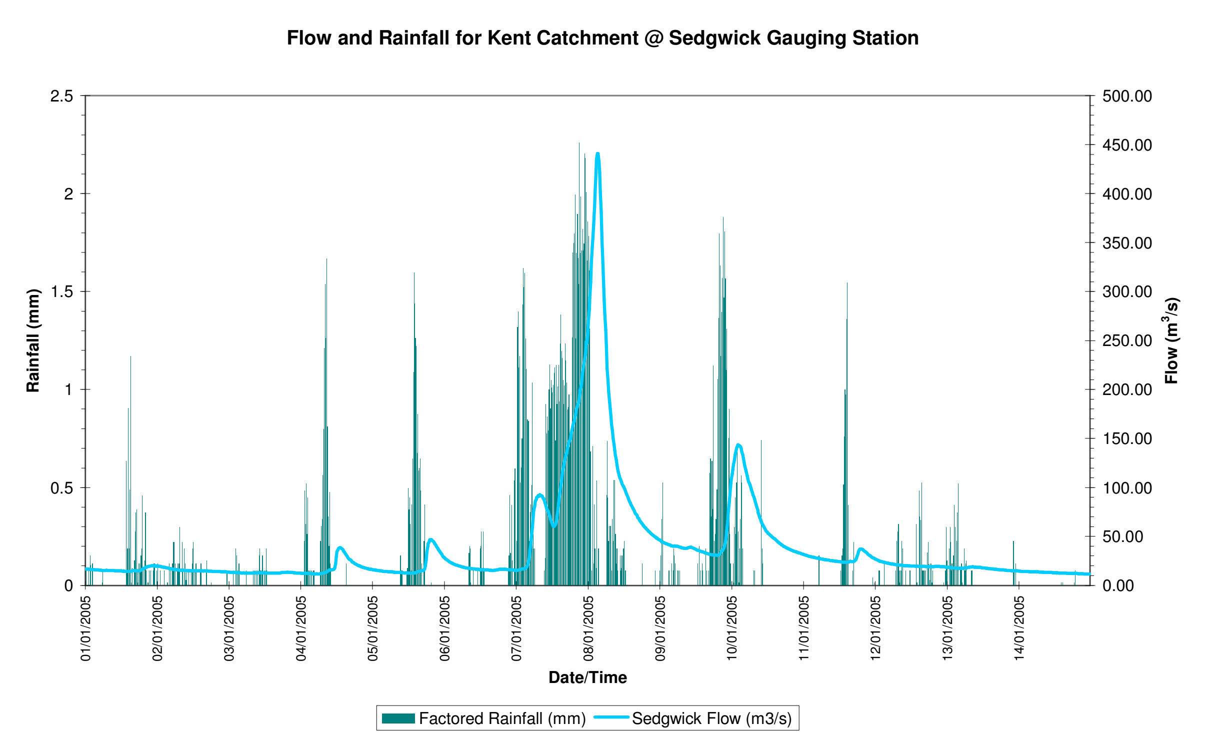


Figure 4-18: Kent Catchment Runoff



4.9 Historical Perspective

Over the last two hundred or so years, there have been a number of flood events most notably in locations such as Appleby, Carlisle, Cockermouth, Kendal and Keswick. The principal floods are listed in Table 4-9.

Table 4-9: Notable floods

Location	Years
Appleby	1822, 1856, 1899, 1928, 1968, 1995, 2005
Carlisle	1771, 1822, 1856, 1925, 1931, 1968, 2005
Cockermouth	1852, 1856, 1898, 1932, 1938, 1954, 2005
Kendal	1898, 1874, 1954, 1985, 1995, 2004, 2005
Keswick	1852, 1856, 1898, 1932, 1938, 1954, 2005

Many of the events in Table 4-9 occurred prior to the construction of the flow gauging stations. Hence, they are only recorded in newspaper articles or similar, or by flood marks such as the ones at Eden Bridge in Carlisle. Such information was collated and is included in Appendix 5. It provides a historical perspective to the flooding in 2005 but it does not take account of the changes that have occurred in the catchments, the floodplains or the rivers. An example of a catchment scale change that has taken place since the 1700s is construction of the reservoirs. Other more local changes include the construction of houses and flood defences.

Photograph 4-1: Flood Levels on Eden Bridge

From the flood records for Eden Bridge, which include the flood marks and a staff gauge maintained by the City Council between about 1850 and the 1930s, the 2005 flood appears to be the highest recorded. It was more than 1m higher than the notable floods of 1771, 1822, 1856, 1925 and 1968. This gives some credence to the estimate of 175 to 200 year (0.57% - 0.5%) for its return period and may even indicate that it is an underestimate.

At the Appleby gauge, the maximum recorded level of 128.64m AOD suggests that the 2005 event is slightly larger than that of March 1968. It is worth noting that the difference in magnitude between these events in Appleby is much less than in Carlisle.

The flood alleviation scheme at Kendal was designed to pass a flow of 280m^3/s, which is based on the 1954 event. From the flow measurements during the 2005 event, the peak flow was less than this; refer to Table 4-5. The 2005 flood is likely to be the fourth largest in the past 200 years after those of 1898, 1874 and 1954. However, a comparison of recent flood levels with historic ones at Kendal is made difficult by the increases in the channel capacity of the Kent resulting from the Kendal Flood Alleviation Scheme (constructed in the 1970s).

It is more difficult to be definitive for Cockermouth and Keswick. However, it is likely that the 2005 event was not as large as say, that of 1938 or 1898.

4.10 Hydrometric Performance

4.10.1 Rain gauges

There are a number of concerns regarding the accuracy of the gauged rainfall data, namely: -

- the accuracy with which the gauge measures rainfall at that location
- how representative that location is of the surrounding area

Recent research (Evaluation of Tipping Bucket Rain Gauge Performance & Data Quality W6-048/S) suggests that, when there are strong winds, automatic tipping bucket gauges may under record rainfall relative to the standard manual Met Office daily gauges. This is believed to be related to the aerodynamic performance of the former and it should be noted that during the 2005 event, the winds were in excess of 50 knots (25 m/s).

Table 4-10 shows a comparison of the two types of gauge. This shows that there were differences and generally the tipping bucket gauges under recorded by on average 8%. It is likely that other factors, such as the calibration of the gauges, may be have an influence.

Table 4-10: Comparison of rainfall over period from 06 Jan 09:00 to 08 Jan 08:59

Ref:	Station Name	Grid Ref	Rainfall Totals (mm)		Difference	
			Daily gauge	TBR	(mm)	%
584190	Carnforth Crag Bank	SD 489 707	29.7	27.4	2.3	8%
606679	Drumburgh	NY 259 602	65.4	57	8.4	13%
586870	Elterwater	NY 329 039	147.8	134.6	13.2	9%
26957	Greenhills Farm	NY 838 320	107.1	92	15.1	14%
8849	Kielder Ridge End	NY 658 959	103.7	88	15.7	15%
073421	Malham Tarn	SD 894 671	75.4	69.4	6	8%
593022	Mungrisdale	NY 360 278	132.9	126.2	6.7	5%
604740	Newton Rigg	NY 493 310	72.6	73.8	-1.2	-2%
580057	Orton Shallowford	NY 626 083	169.7	164.8	4.9	3%
591236	Seascale White Heath	NY 46 18	42.4	40.8	1.6	4%
603741	Walton	NY 530 653	49.4	46.2	3.2	6%
					Average	**8%**

This potential underestimation of rainfall by the tipping bucket gauges means that some of the return periods in Table 4-2 are likely to be underestimates.

The location of the gauges is also an important factor. For example, rainfall increases with altitude but due to the difficulties in locating gauges in hills and mountains, the highest gauges are only at some 360m AOD. By contrast, the tops of the mountains are in excess of 900m and there are significant areas of land above 400m.

Maps 7 and 8 show there is a significant area of high ground at Howgill Fells which is more than 3km from a tipping bucket gauge. This area drains to the Lune and Eden and it experienced some of the higher rainfall totals during the 2005 event; refer to Maps 3 to 6. Another area of high ground which lacks coverage is a small area to the north of Skiddaw. However, there are very significant difficulties in locating and maintaining rain gauges in remote areas of high ground. This is particular so if the areas are also within a National Park or similar landscape designation.

The majority of settlements are covered by tipping bucket gauges connected via telemetry. Map 7 in Appendix 2 shows the location of such gauges together with a buffer of 3km. This shows that approximately 25% of the county has rain gauge coverage. Map 8 in Appendix 2 shows the location of the same gauges with buffers of 6km. At this level, 75% of Cumbria is covered by the network.

The coverage of the rain gauges over Cumbria broadly meets the Environment Agency's levels of service guidelines for flood detection, which set a coverage density target for gauges.

There are other gauges which are not connected to the telemetry network. The coverage increases if these are included, however, only the telemetered gauge data can be used for real time flood warning purposes.

4.10.2 Gauging Stations

Most flow gauging stations measure water level directly, which is then converted to a flow using a stage discharge equation. This is based on the premise that there is a unique relationship between stage and flow, which is true in many but not all cases. The equations are derived either from theoretical equations for the weir or structure, or current meter gaugings of the flow.

At high flows, there are a number of factors that may affect the quality of the stage discharge equation and, hence, the flow. These include:-

- flows which bypasses the site
- change of 'control' between normal and high flows. For example, lower flows may be controlled by the weir but higher ones may be controlled by a downstream bridge
- difficulties in obtaining current meter gaugings during an event

The performance of the gauging stations during the 2005 event was assessed and is shown in Table 4-11. It is predominantly based on information supplied by the Environment Agency.

Table 4-11: Performance of gauging stations

Gauging Station	CEH_Ref	Watercourse	Catchment	Recorded Flow (m^3/s)	Highest on Record	Flows out of bank	Flow greater than highest gauged	Comments on accuracy of stage discharge relationship in Jan 2005
Beetham	73008	Bela	Bela	62	✗	✗	✓	
Calder Hall	74006	Calder	Calder	40	✗	✗	✓	2005 stage was above the structure wing walls
Low Nibthwaite	73002	Crake	Crake	19	✗	✗	✗	
Camerton	75002	Derwent	Derwent	294	✓	✗	✓	
Low Briery	75009	Greta	Derwent	270	✓	✗	✓	Low Briery is now treated as a level only station confidence in the figures is low
Ouse Bridge	75003	Derwent	Derwent	146	✓	✓	✓	2005 flow likely to be an underestimate
Portinscale	75005	Derwent	Derwent	158	✓	✓	✓	This site is likely to have been significantly bypassed in 2005
Southwaite Bridge	75004	Cocker	Derwent	87	✓	✓	✓	Some bypassing occurred in 2005. Previous gaugings show +/- 20% variation in high flows
Thirlmere	75001	St John's Beck	Derwent	103	✓	✓	✓	Significant bypassing in 2005
Threlkeld	75007	Glendermackin	Derwent	80	✗	✗	✓	Although just in bank at the catual gauge, this site would have been bypassed in 2005
Duddon Hall	74001	Duddon	Duddon	Jan 2005 flow was not the highest flow in 2005				
Ulpha	74008	Duddon	Duddon	65	✗	✗	✗	Although within the gauged range, there are limited gaugings at this stage. These show significant variations
Burnbanks	76001	Haweswater Beck	Eden	28	✗	✗	✓	Although the flow is above the highest gauging, it is contained within the structure
Coal Burn	76011	Coal Burn	Eden	3	✗	✓	✓	
Cummersdale	76809	Caldew	Eden	193	✓	✓	✓	Substantial out of bank flow occurred in 2005 flood. Further work on the stage discharge equation is taking place in 2006
Dacre Bridge	76811	Dacre Beck	Eden	49	✗	✗	✓	
Eamont Bridge	76004	Lowther	Eden	198	✓	✓	✓	In 2005, flows were out of bank and bypassed on the right bank
Great Corby	76810	Eden	Eden	854	✓	✓	✓	In 2005, there would have been minor out of bank flow. Further work has already been undertaken to improve the stage discharge equation

Gauging Station	CEH_Ref	Watercourse	Catchment	Recorded Flow (m^3/s)	Highest on Record	Flows out of bank	Flow greater than highest gauged	Comments on accuracy of stage discharge relationship in Jan 2005
Great Musgrave Bridge	76806	Eden	Eden	194	✓	✓	✓	In 2005, the flow was significantly out of bank. However based on gaugings during the flood, a recent improved rating has been derived
Greenholme	76008	Irthing	Eden	278	✓	✓	✓	In 2005, flows were out of bank and affected by the high levels in the Eden
Harraby Green	76010	Petteril	Eden	83	✓	✓	✓	In 2005, flows were out of bank mainly on right bank. Modelling to improve the high flow rating is planned
Kirkby Stephen	76014	Eden	Eden	129	Equal	✓	✓	Although the 2005 flow was out of bank it was only about 10% above the highest gauged flow
Pooley Bridge	76015	Eamont	Eden	108	✓	✓	✓	Substantial out of bank flow in 2005
Sheepmount	76007	Eden	Eden	1520	✓	✓	✓	Subsequent review of the rating using modeling has shown it to be reasonable
Temple Sowerby	76005	Eden	Eden	391	✓	✓	✓	A review of the rating using modeling is planned
Udford	76003	Eamont	Eden	295	✓	✓	✓	A review of the rating using modeling is planned
Bleach Green Weir	74003	Ehen	Ehen	41	✗	✗	✓	The 2005 flow was contained within the structure
Braystones FMS	74005	Ehen	Ehen	64	✗	✗	✗	
Bullgill	75017	Ellen	Ellen	50	✓	✓	✓	There was significant bypass flow on left bank during Jan 2005
Cropple How	74007	Esk	Esk	107	✗	✓	✓	There was significant out of bank flow in 2005
Canonbie	77002	Esk (Scotland)	Esk (Scotland)	469	✗	✗	✓	The 2005 flows were in bank although substantially more than the highest gauged
Galesyke	74002	Irt	Irt	22	✗	✓	✗	Some out of bank flow may have occurred in 2005 but it was below highest gauged flow
Mint Bridge	73011	Mint	Kent	115	✓	✗	✓	
Sedgwick	73005	Kent	Kent	441	✓	✗	✓	Recent work suggests high flows are over-estimated.

Gauging Station	CEH_Ref	Watercourse	Catchment	Recorded Flow (m^3/s)	Highest on Record	Flows out of bank	Flow greater than highest gauged	Comments on accuracy of stage discharge relationship in Jan 2005
Sprint Mill	73009	Sprint	Kent	83	✓	✗	✓	The 2005 flows were in bank, however, previous gaugings suggest that high flows may be underestimated
Victoria Bridge	73012	Kent	Kent	240	✓	✗	✓	Recent work and comparison with Sedgwick suggests high flows are underestimated
Eel House Bridge	73006	Cunsey Beck	Leven	9	✗	✗	✗	Although the 2005 flow is less than the highest gauged flow, there is significant variation in the highest gaugings
Jeffy Knotts	73014	Brathay	Leven	79	✓	✗	✓	The 2005 flow is significantly above the highest gauged flow
Newby Bridge FMS	73010	Leven	Leven	110	✗	✗	✗	

Note: Peak flows shown in this table are flows taken from the Environment Agency's hydrometric archive (at time of writing). These flows may be adjusted in light of recent studies, these flows are used in Table 4-5.

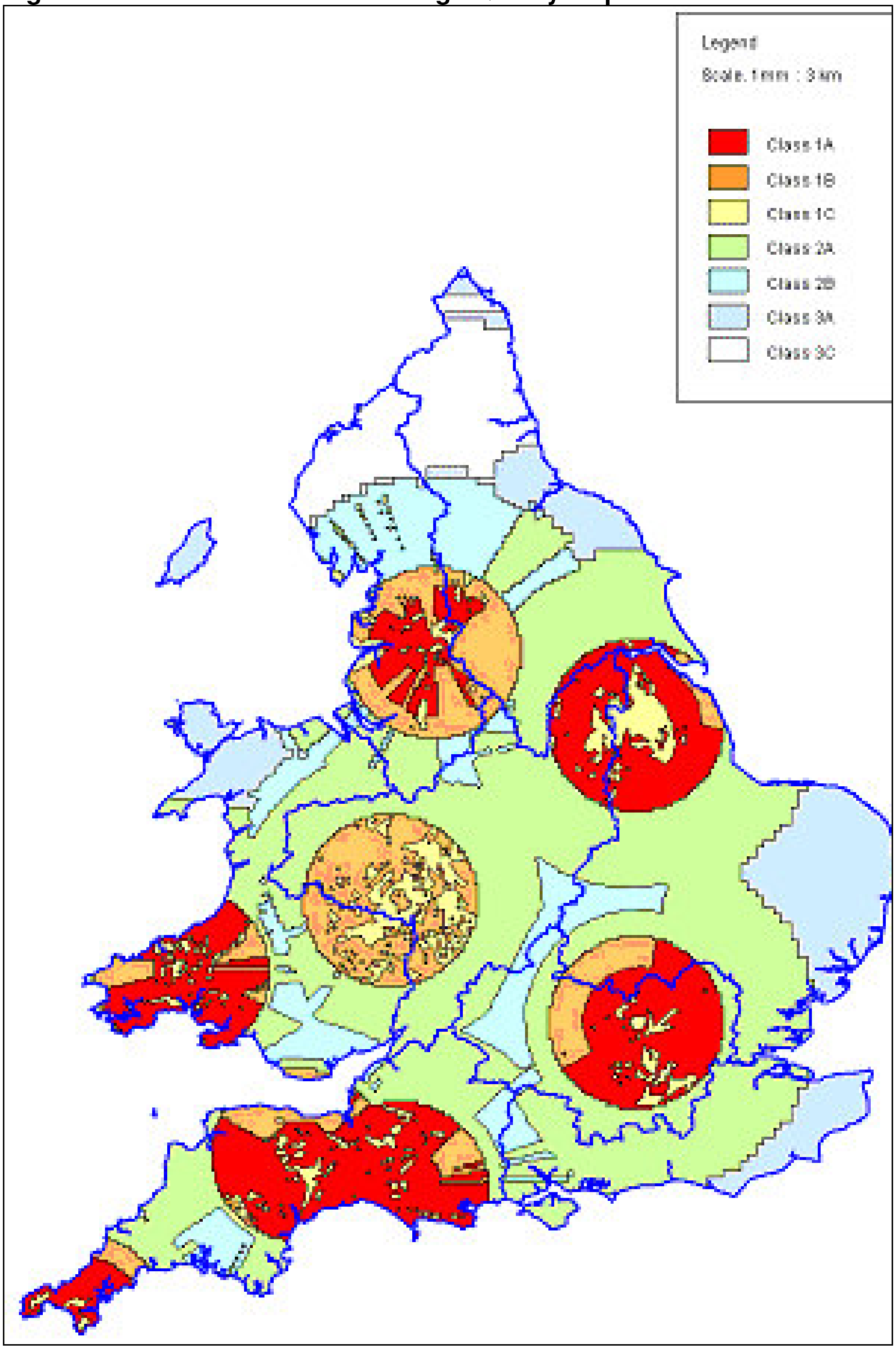
4.10.3 Rainfall Radar

The UK rainfall radar network provides additional valuable information on rainfall and timing.

Figure 4-19 shows that the radar data in the south of Cumbria is Class 2B, which is quite low quality. In the north of the county, the radar data is Class 3C, which is the lowest quality. Table 4-12 explains the different quality classes.

As discussed in Section 3, the main reason for this is the distance from the nearest radar site at Hameldon Hill, which is located to the south of Burnley. One effect of this is that the scanning beam can be higher than the precipitation.

Figure 4-19: Radar Network Coverage Quality Map



Source: R&D Rainfall Measurement and Forecasting Guidelines, July 2002

Table 4-12: Radar Quality Index Classification Scheme

Range (km)	Data Resolution (km)	Quality Class	POD[1] (%)	Basis for classifier	Comments
0-50	1	1 (1A)	94	Beam < 500m	Highest quality data. Detection rate of close to 100% for all types of rainfall.
0-50	1	2 (1B)	91	Beam > 500m	As 1A, but greater beam height will increase likelihood of errors related to below beam effects such as lateral drift, screening of low level precipitation.
0-50	1	3 (1C)	91	Clutter affected	Note: Quality dependent on new developments in clutter suppression/data processing in clutter affected areas.
50-100	2	4 (2A)	89	Beam < 1000m	
50-100	2	5 (2B)	86	Beam > 1000m	
100-250	5	6 (3A)	82	Beam < 2000m	
100-250	5	7 (3B)	73	Beam > 2000m	Low quality data, only deep precipitation will be detected.
		8 (3C)			Lowest quality data

[1] POD – Probability of Detection
(Source: R&D Rainfall Measurement and Forecasting Guidelines, July 2002)

The Environment Agency's review of the event includes an assessment of rainfall totals from the rainfall radar. Due to the quality issues described above, these figures do not compare well with the totals from the network of rain gauges.

During January 2005, the accurate detection of rainfall is further complicated by the presence of orographic rainfall. With the 'feeder' clouds at a very low level, some of the rainfall will have occurred below the radar beam; particularly in the north of the county.

4.10.4 Estimation of rainfall and flood probabilities

The Flood Estimation Handbook provides methods to estimate the probabilities of both rainfall and flow at a given location in Great Britain and Northern Ireland.

It is worth noting that the estimation of rainfall probabilities for the 2005 event was carried using out the Depth Duration Frequency (DDF). This is built up from data from a large number of tipping bucket and daily gauges to form a model with a 1km resolution. It takes account of aspect and altitude. The coverage of the gauges in Cumbria is slightly poorer than for other areas of England. In addition, for Cumbria, small variations in rainfall amount or location can result in significant changes to the estimated probabilities.

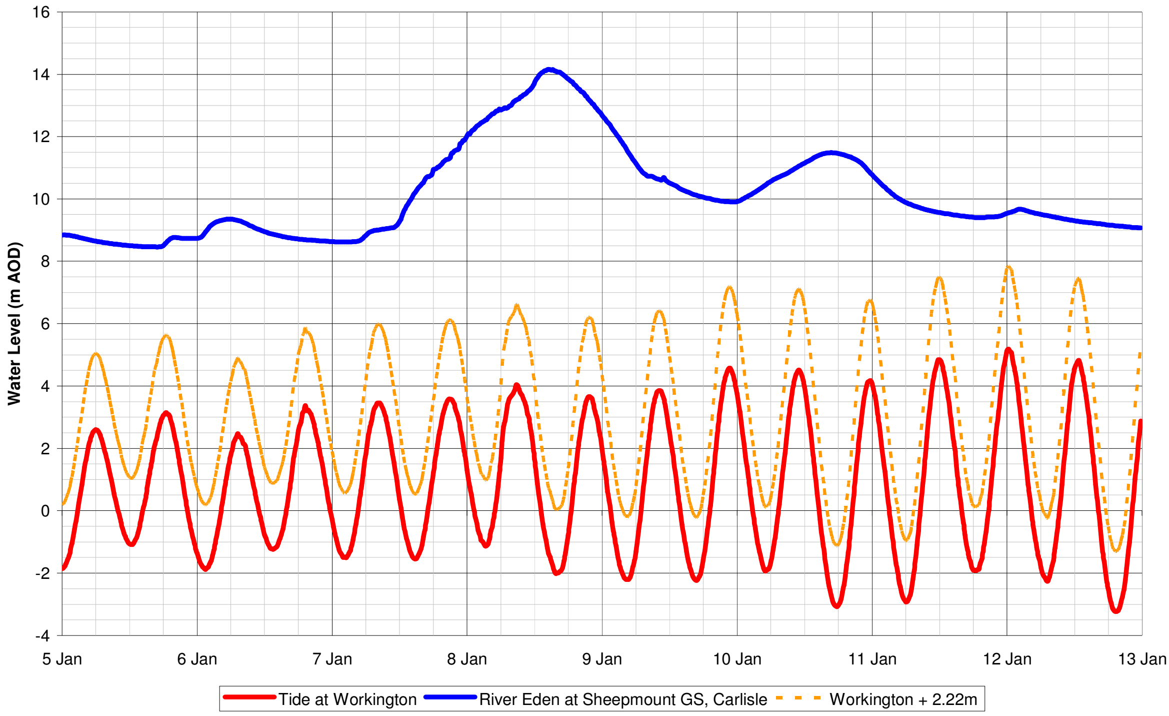
The probabilities of the peak flows were calculated using several different methods. As is emphasized in the handbook, the quality of estimate is dependent on the quality of the available data.

4.11 Tidal Effects

The effect of high tides in the Solway Firth on the River Eden at Carlisle was raised by local residents and media after the floods.

Figure 4-20 shows a comparison of the tide levels at Workington and the river level at the Sheepmount Gauging Station on the River Eden in Carlisle. The Environment Agency's tidal flood forecasting system shows that tide levels in the tidal reach of the River Eden are typically about 2.22m above those at Workington; this is also shown on Figure 4-20. Prior to the event, the peak levels in the River Eden are at least 2m above the tide. The peak river level is about 8m above the tide.

Figure 4-20: Comparison of tide levels with River Eden levels



Further analysis of the tidal effect was carried out using a computer model. The model indicates that the tidal effect is limited by a weir near Davidson's Bank and that tide levels in excess of those in January 2005 would have no effect on the River Eden levels in Carlisle.

There are a number of areas along the Cumbrian coast that are at risk of flooding from extreme tides, although they were not affected in 2005.

4.12 Geomorphology

During the 2005 event, significant amounts of erosion and deposition of sediments occurred in the Cumbrian rivers; these were typically gravels. In some cases, this caused minor changes in the course of some rivers and damage to roads or other infrastructure. Such natural processes are expected in times of peak flows.

However, from subsequent studies and observations, no evidence was found that the deposition of sediment had a significant impact on the amount of flooding or that there are unusual or unexpected patterns of erosion and deposition.

5 FLOOD WARNING & FORECASTING

5.1 Introduction

This section covers the flood forecasting and warning aspects of the 2005 event. It considers the number and location of the warnings that were issued, the performance of the Automatic Voice Messaging System (AVM) as the prime method of dissemination and the availability and performance of flood forecasting.

As stated in Section 2.2, it does not cover such aspects in detail as they are dealt with in the Environment Agency's publication 'A review of the floods in northern England and North Wales January 2005'.

5.2 Flood Warning Areas (FWAs)

The Environment Agency issue flood warnings for defined Flood Warning Areas. In January 2005, the relevant Flood Warning Areas which were affected by flooding are listed in Table 5-1.

Table 5-1: Flood Warning Areas pre January 2005

Location	Flood Warning Areas
Appleby	Existing FWA
Carlisle	Existing Carlisle FWA
	Existing Denton Holme FWA
Cockermouth	Existing FWA
Eamont Bridge	Existing FWA
Eden Valley	Existing FWA
Egremont	Existing FWA
Kendal	Existing FWA
Keswick	Existing FWA

Not all areas at risk of flooding are within a defined Flood Warning Area. In Cumbria, such locations include Penrith, Ambleside and Wigton. The current Flood Warning Areas are locations where it is possible to give timely and accurate flood warnings. The Environment Agency are working to expand the coverage of their flood warning service in the future.

5.3 Flood Warnings Issued

A flood warning is issued by the Environment Agency's Flood Warning Duty Officers when river levels are forecast to meet the criteria set for that particular area. The process is not automatic and allows the duty officer to assess the current flood conditions and the available forecasts. The primary method used by the Environment Agency to disseminate flood warnings was the Automatic Voice Messaging system, which makes phone calls to all of the numbers registered within a specific area. Warnings are also issued via the media, through the floodline telephone listening service and the internet.

Table 5-2 lists the times at which the flood warnings were issued in the particular areas.

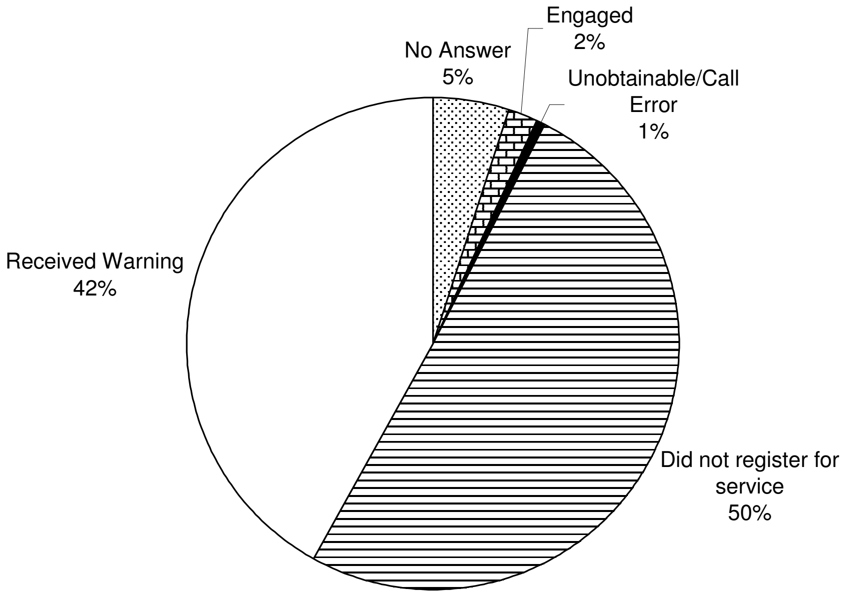
Table 5-2: Flood Warnings issued during the January 2005 flood event

Area	Warning Issued	
	Date	Time
Farmers	07/01/2006	11:10
Appleby A	07/01/2006	13:01
Farmers	07/01/2006	13:49
Keswick A	07/01/2006	15:56
Carlisle A	07/01/2006	17:18
Kendal A	07/01/2006	17:19
Cockermouth A	07/01/2006	18:22
Eden Valley	07/01/2006	18:32
Eamont Bridge	07/01/2006	21:50
Appleby B	07/01/2006	21:56
Keswick B	07/01/2006	22:14
Keswick C	07/01/2006	23:32
Keswick D	07/01/2006	23:59
Kendal B	08/01/2006	00:18
Carlisle B	08/01/2006	00:48
Kendal C	08/01/2006	01:17
Cockermouth C	08/01/2006	01:32
Denton Holme	08/01/2006	02:22
Carlisle D	08/01/2006	03:14
Carlisle C	08/01/2006	05:02
Cockermouth D	08/01/2006	07:13
Cockermouth B	08/01/2006	07:15
Carlisle Severe	08/01/2006	10.44
Denton Holme Severe	08/01/2006	10.44

Table 5-3 shows the percentage of properties that accepted the offer of the free AVM service. It also shows the percentage of those that received the warning during the 2005 event.

Figure 5-1 gives the breakdown of the responses from the properties registered with AVM.

Figure 5-1: Breakdown of responses from the 4882 properties within the Flood Warning Areas



5.4 Flood Forecasting

The Environment Agency use a range of different flood forecasting tools for the rivers in Cumbria. These fall into the following four main types: -

- Simple trigger forecasts, which use the rate of rise in river level during the previous x hours to advise the level in y hours time.
- Level to level correlations, which are derived by correlating flood peaks at one or more upstream location with those at the site of interest. These correlations, which are normally related to level and sometimes flow, are used in ‘real-time’ to predict levels at the subject site.
- Transfer function models, which use a simple mathematical relationship between measured flow and measured and/or forecast rainfall to predict future flows.
- Complex forecasting models, which are based on computer modeling of the river upstream of the forecast site. These include many different inputs and can forecast at more than one location.

Table 5-3: AVM Statistics (figures correct January 2005)

Flood Warning Area	Number of properties offered AVM[1]	% properties taken up service[2]	%calls made[3]	% Registered properties received warning[4]
Farmers	12	100%	100%	**91%**
Carlisle A	1	100%	[5]	[6]
Carlisle B	18	72%	100%	**77%**
Carlisle C	186	47%	100%	**84%**
Carlisle D	1133	54%	100%	**87%**
Denton Holme	1652	38%	100%	**80%**
Appleby A	79	70%	100%	**82%**
Appleby B	137	68%	100%	**92%**
Cockermouth A	4	75%	100%	**66%**
Cockermouth B	20	75%	100%	**80%**
Cockermouth C	8	50%	100%	**100%**
Cockermouth D	444	63%	100%	**81%**
Keswick A	6	100%	100%	**100%**
Keswick B	66	20%	100%	**85%**
Keswick C	194	76%	100%	**91%**
Keswick D	260	49%	[7]	**85%**
Kendal A	75	46%	100%	**80%**
Kendal B	169	35%	100%	**83%**
Kendal C	345	50%	100%	**85%**
Eden Valley	18	72%	100%	**100%**
Eamont Bridge	55	76%	100%	**98%**

[1] All properties within a flood risk area are offered the AVM service
[2] Percentage of properties within the flood warning area accepting the AVM service
[3] Percentage of properties registered for the AVM service that the AVM system called
[4] Percentage of properties registered for the AVM that received flood warning
[5] The property was called by a member of Environment Agency staff
[6] The property received its flood warning call from a member of Environment Agency staff
[7] Data not available

During the January 2005 flood, simple trigger forecasts were available for the following sites:

- Appleby
- Denton Holme - River Caldew in Carlisle
- Egremont
- Harris Footbridge - Cockermouth
- Sheepmount - Carlisle
- South Street Footbridge - Cockermouth

Transfer function forecasts were available for the following sites:

- Cummersdale - River Caldew, Carlisle
- Low Briery - Keswick
- Victoria Bridge - Kendal

Level to level correlations or flow to flow correlations were available for the following sites: -

- Appleby
- Denton Holme - Carlisle
- Eamont Bridge Farm
- Great Corby - Warwick Bridge, upstream of Carlisle
- Low Briery - Keswick
- Sheepmount - Carlisle
- Victoria Bridge - Kendal

In addition, the Eden ISIS real-time hydrodynamic model for Carlisle was available. This uses inputs from the Temple Sowerby and Udford Gauging Stations, and Muskingum Cunge routing to generate flows at Great Corby. Downstream of Great Corby, it uses a full ISIS hydrodynamic model with further inflows from the gauging stations at Cummersdale, Harraby Green and Greenholme. This provides forecast levels at a number of locations up to 12 hours in the future. This is described in the paper described by *Spencer et al* which is included in Appendix 6.

5.5 Performance of Flood Forecasts

5.5.1 Introduction

Following the January 2005 event, the performance of the flood forecasting models was reviewed in a series of separate studies. The following sections summarise the key findings.

5.5.2 Simple Triggers

The simple trigger forecasts generally performed well and gave at least 2 hours lead time.

5.5.3 Transfer Function Models

The performance of the three transfer function models varied and is summarised in Table 5-4.

Table 5-4: Transfer Function Model Performance

Model	Performance
River Greta at Low Briery (Keswick)	• Performed poorly • Even after re-calibration, the model did not forecast the January 2005 flood well although performed better on other floods
River Kent at Victoria Bridge (Kendal)	• Performed reasonably • Timing was late on the higher flood warning threshold levels
River Caldew at Cummersdale (Carlisle)	• Performed poorly • However, poor performance was mainly due to the quality of the rainfall radar for this catchment

5.5.4 Correlations

In 2005, the peak levels exceeded the previously recorded ones at virtually all locations where correlations were used. The following correlations performed poorly and generally under predicted the peak: -

- Appleby
- Sheepmount - Carlisle
- Denton Holme - Carlisle
- Low Briery - Keswick
- Great Corby - Warwick Bridge, upstream of Carlisle

The correlations for Eamont Bridge and Low Briery were satisfactory.

5.5.5 ISIS Real-time Hydrodynamic Model

Spencer et al (2006) describe the performance of all the forecasting models for Carlisle, particularly the ISIS one. The conclusion is that the model performed well up to a stage of 5.5m at the Sheepmount Gauging Station. Thereafter, it became progressively worse and did not predict much of the final surge towards the peak. The flood peak was underestimated by some 1m and $450m^3/s$. Since 2005, a number of improvements have been made to the model; these are outlined in Section 7.2.2 and Appendix 6.

6 DESCRIPTION OF FLOOD IMPACTS

6.1 Introduction

This section covers the impact and mechanisms of flooding of both residential and commercial properties at various locations. For ease of reference these areas have been grouped into District Council areas. These areas are shown in Figure 6-1.

Figure 6-1: District Council Boundaries

No areas within the boundaries of Copeland Borough Council or Barrow in Furness Borough Council flooded during the event.

It also covers the damages to business and infrastructure, and the social impacts of flooding.

Surveys of wrack levels were carried out after the event for some areas of Cumbria. The areas surveyed are listed in Table 6-1. The survey results are held at the Environment Agency office in Penrith.

Table 6-1: Areas where wrack levels were surveyed post January 2005 event

Survey ref	Area covered	Survey ref	Area covered
PO1	Kendal and Burneside	PO8	Morland
PO2	Soulby	PO9	Eamont Bridge
PO3	Kirkby Stephen	PO10-13	Carlisle (Eden, Caldew & Petteril up to Low Crosby)
PO4	Stockdalewath	PO14-17	Maryport and Ellen Valley
PO5	Warcop	PO18	Wigton
PO6	Great Asby	PO19	Appleby
PO7	Dalston	PO22	Further areas of Carlisle
N/a	Cockermouth	N/a	Keswick

6.2 Allerdale Borough

6.2.1 Blennerhasset

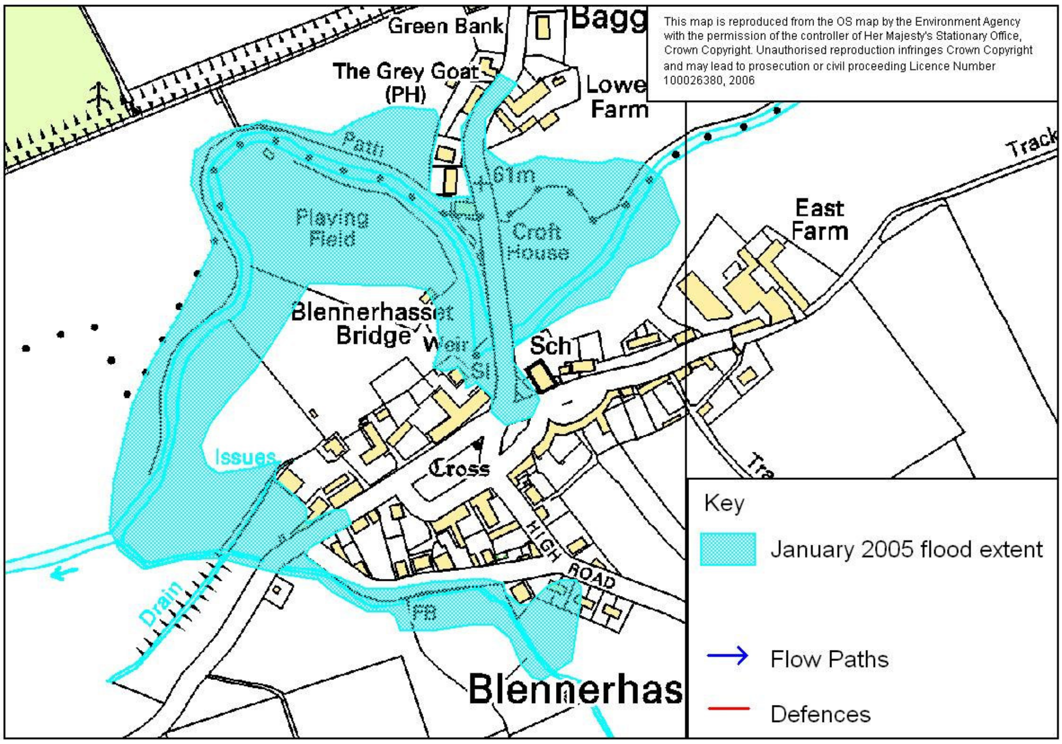
No. of properties affected: 6 Cause of flooding: River Ellen and surface water Key Points: • Croft House flooded

Blennerhasset lies on the River Ellen and is protected by an embankment on the right bank.

The flood waters extended between 50 and 100m into the field on the right bank. Both properties in Croft House flooded from the fields to the east of the bridge. This indicates that the embankment was overtopped or breached. It is not known if the bungalow further up the rood flooded. According to the residents, the playing fields on the left bank flooded and wrack marks were visible.

There may have been some surface water flooding higher up in Baggrow. There were reports of at least one house being flooded in the south west part of the village. However, during a site visit, it appeared that at least three houses had flooded because they were unoccupied and heavily sandbagged. Some of this flood water may have come from Low Woodnook Beck. Further upstream, the council houses on High Gate were flooded; we spoke to the lady in No. 3 High Gate and she confirmed this.

Figure 6-2: Flood outline in Blennerhasset



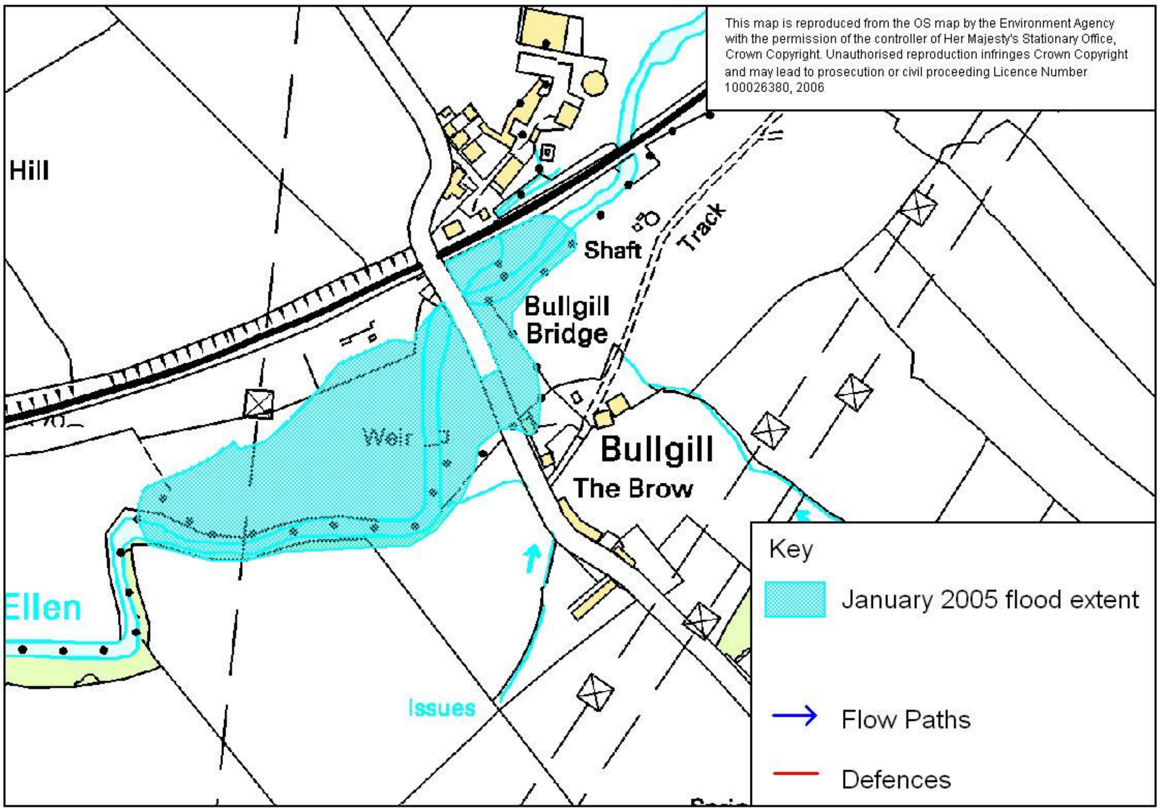
6.2.2 Bullgill

No. of properties affected: 3 Cause of flooding: River Ellen Key Points: • The railway was undermined by the flood waters

Bullgill is on the River Ellen.

On the day of the visit, there was a clear wrack mark just to the left of the pylon on the right bank downstream of the road bridge. This is approximately opposite the gauging station. According to the farmer, a number of properties on the right bank and the basement of Main Band House on the left bank flooded. It was subsequently confirmed that this was the case. The railway was also undermined.

Figure 6-3: Flood outline in Bullgill



6.2.3 Cockermouth

No. of properties affected: 149
Cause of flooding: Rivers Derwent and Cocker; rising water table and highway drainage
Key Points:

- The Rivers Cocker and Derwent converge in the town
- Flood defences were constructed in 1998 along the Cocker and the left bank of the Derwent
- The main source of the flooding was the overtopping of the defences by the Derwent
- Approximately 112 of the properties flooded in the town were flooded by the Derwent, the remaining 37 were flooded by the Cocker
- There are no raised defences in the Gote area
- Jennings Brewery flooded

Flood Warnings can be triggered by high levels in either the River Cocker or Derwent. Flood Warnings were issued on 7 January at 1822hrs, 0715hrs and 0134hrs, and 0713hrs on 8 January, for different areas of the town.

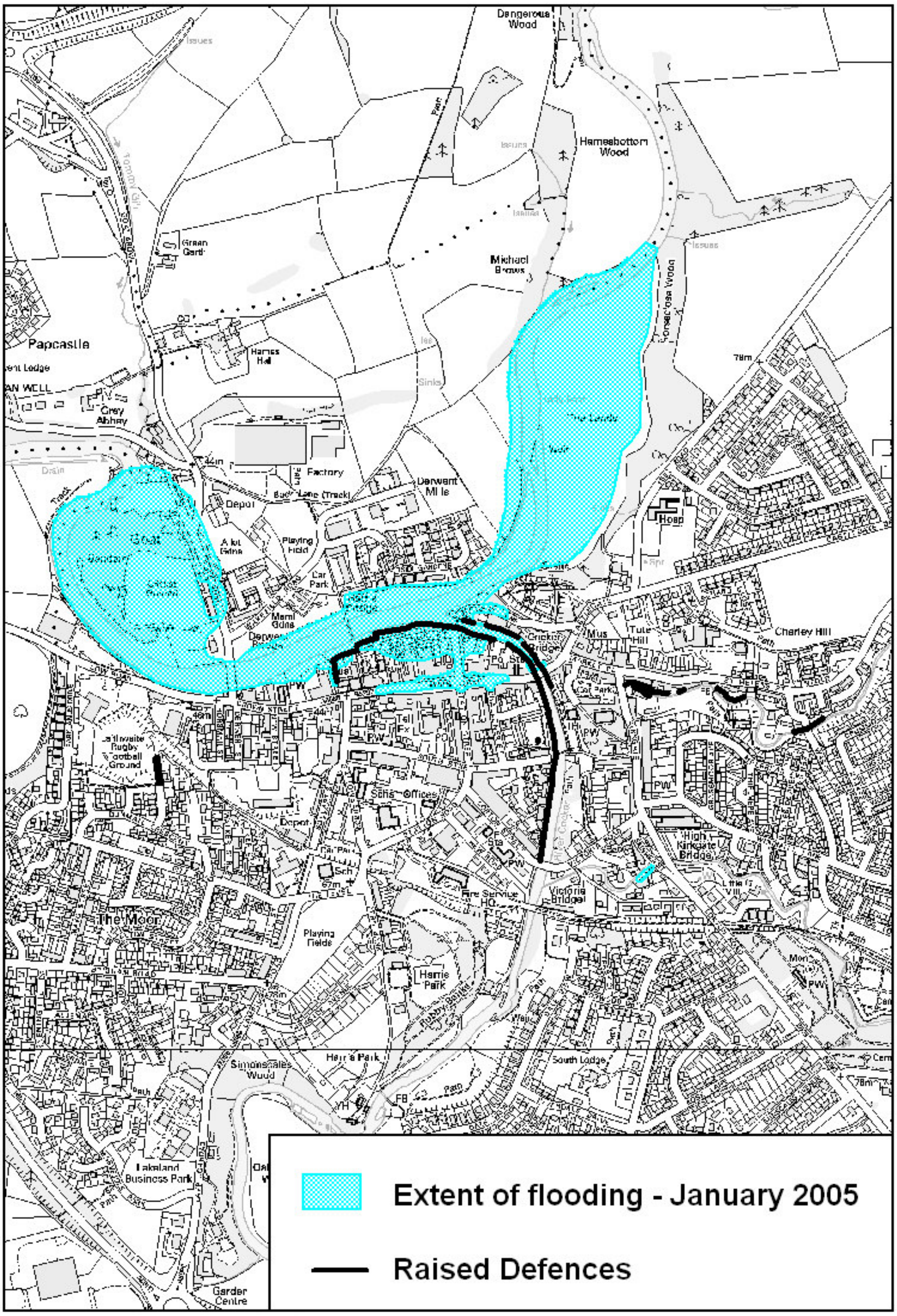
6.2.3.1 The Gote Area

The Gote area has historically flooded from the River Derwent. This was thought to have been exacerbated by a large weir which has since been removed. There are no flood defences in the area.

The first flooding affected the low lying area of Sandair and was caused by the rising water table. Shortly afterwards, the area in front of the allotment gardens started to flood, initially from highway drainage which discharges to the river. River levels continued to rise and reached the rear of Gote Road; water subsequently flowed through the properties onto Gote Road. At the peak at 0930hrs, a flow route was established via the entrance to the cricket ground. At roughly the same time, another flow route was established to the river from the north end of Gote Road.

Some 34 properties suffered internal flooding and the maximum depth of water in the road was approximately 0.9m.

Figure 6-4: Flood outline in Cockermouth



6.2.3.2 Town Centre and Waterloo Street

In 1998, raised defences were constructed along the River Cocker and the left bank of the Derwent to protect the town centre. These were to a design standard of 1 in 100 years (1%).

Although the River Cocker was in spate, the majority of the flooding in Cockermouth was due to the overtopping of the raised defences on the left bank of the Derwent; the defences did not breach.

Photograph 6-1: Flooding in Waterloo Street

(Source: bbc.co.uk/cumbria)

Flooding initially occurred to a property at the confluence, by the footbridge in Waterloo Street. This was at 0000hrs on 7 January and was due to a faulty stop log, which is owned by a resident.

At 0720hrs, water started to flow into Waterloo Street and ponded behind the defences; it was unable to return to the river. Anecdotal evidence suggests that some of the initial flooding occurred due to missing or blocked outfall flap valves. By 0830hrs, the flooding extended onto the northern half of Main Street and by 1230hrs it covered the whole of the street to a depth of 100mm. One shop in Main Street took action to prevent flooding before the water lapped up to the door sills. Parts of Waterloo Street experienced flooding up to a depth of 0.9m.

The riverside wall along Waterloo Street, which was raised as part of the defence scheme, overtopped at 0730hrs on 8 January. Prior to this, a faulty or open flap valve in the wall resulted in flooding of a patio.

The left bank at Waterloo footbridge overtopped during the event. Water was seen coming through the gap at the footbridge, where the riverside steps have wooden stoplogs. Water flowed from along Waterloo Street in a westerly direction and spread southwards along High Sands Lane to flood Main Street.

Photograph 6-2: Flooding in Cockermouth Town Centre

(Source: bbc.co.uk/cumbria – taken by Tony Terry)

The water which flowed down Waterloo Street, behind Graves Mill, collected in the walled car park at the end of Waterloo Street. The wall appears to have blocked the returning flow until a small gap was cleared of debris and the level in Waterloo Street dropped. Residents state that this was always the route that water returned to the river.

The Graves Mill embankment did not appear to have been overtopped, although the peak water level was within 100 to 150mm of its crest.

Flood waters came through the garden of a house upstream of Graves Mill. It is understood to have some defence measures in place. Further flow may have come out of bank between here and Whartons Mill.

Flood waters came up Low Sands Lane almost as far as Main Street and entered the garden of Wordsworth House. Wrack marks were seen on the drive of 10 Low Sands Lane. These and the resident of that property suggest that water reached approximately the damp-proof course of the extension to the Trout Hotel.

A resident of Low Sands Lane stated that flood waters seeped through the high masonry riverside wall at the cul-de-sac end of Victoria Court. It flowed to the residential areas upstream of the Waterloo footbridge.

On the right bank, upstream of the Waterloo footbridge, it appears that the river may have come out of bank at a gate. A property was sandbagged and discarded carpets were seen in the backyard.

Photograph 6-3: Flood waters rising at The Riverside Restaurant

The yard of the property on the right bank, upstream of the footbridge at Cocker Lane, flooded to a depth of between 0.6 and 0.8m. Due to its elevated threshold, the property was not flooded. The resident estimated that the water level peaked at approximately 0730hrs on 8 January.

Staff from the Environment Agency were in attendance during the flooding. Allerdale Borough Council staff were on site from 0200 to 0300hrs giving out sandbags to householders. Cumbria County Council staff also provided sandbags from their highways depot.

113 properties were flooded in Waterloo Street, with a further 2 elsewhere in the town centre. Jennings Brewery also flooded.

6.2.4 Keswick

No. of properties affected: 198
Cause of flooding: River Greta; surface water; sewage, when UU pumping station failed; Cuddy Beck and Cuddy Beck tributary surcharged.
Key Points:

- This was the largest event on record
- The Greta overtopped its defences on the right bank at High Hill and Crosthwaite Road
- The United Utilities' pumping station at Greta Grove failed
- Many residents had to be evacuated from their homes by the emergency services

Keswick is protected from the River Greta by flood walls and embankments on the right bank along High Hill and Crosthwaite Road, and on the left bank between Main Street and the rugby club ground. The defences, which were built in 1985, provide protection to a 1 in 50 year standard. The only flood defence in Keswick which requires operating in times of flood is stoplogs across a river access point next to Greta Bridge; these were in place during the event.

The town has a long history of flooding, with the last major flood event being 21 December 1985. The event which occurred in 2005 was the largest on record and the peak level at the Low Briery Gauging Station was 300mm higher than that in 1985.

Photograph 6-4: High Hill in Keswick in the early hours of 8 January

Flood Warnings were issued on 7 January at 1556hrs, 2214hrs, 2332hrs and 2355hrs for different areas of the town. The flooding commenced at 1900hrs, N/a, 2330hrs (on 8 January) and 2200hrs (on 7 January) respectively.

Photograph 6-5: Flood waters overtopping a wall in Keswick

In Keswick, the Greta and its tributaries rose significantly between the morning of 7 January and the early hours of 8 January. The defences on High Hill were overtopped by 150mm and the embankment in Crosthwaite Road by 0.5m. Water that overtopped the Crosthwaite Road embankment joined Crosthwaite Beck. The exterior wall at the Keswick Youth Centre, which acts as a flood defence, also leaked badly.

Surface water and sewage flooding affected the Elliot Park area when the United Utilities' pumping station at Greta Grove failed. The surcharged drains flooded properties to a depth of 1m.

Cuddy Beck and Cuddy Beck Tributary are designated COWs, due to their long history of flooding problems. Both these culverted watercourses surcharged, causing water to flow overland and flood properties on Millfield Gardens, Windebrowe Avenue and Penrith Road.

Penrith Road was initially flooded from surface water from Cuddy Beck flowing into the River Greta and surface water runoff from the surrounding roads and fields. The situation was made worse when a tree became lodged on the footbridge next to the war memorial at around midnight. This caused the defences on the left bank to be overtopped. The footbridge gave way at around 0030hrs. Further properties were flooded in Penrith Road when the river overtopped a dwarf highway wall opposite Upper Fitz at 0200hrs on 8 January.

Photograph 6-6: Damaged footbridge over the River Greta

(Source: bbc.co.uk/cumbria – taken by Dave Lewis)

The embankment on Crosthwaite Road overtopped from Fitz Park, resulting in a large volume of water running down the road towards High Hill.

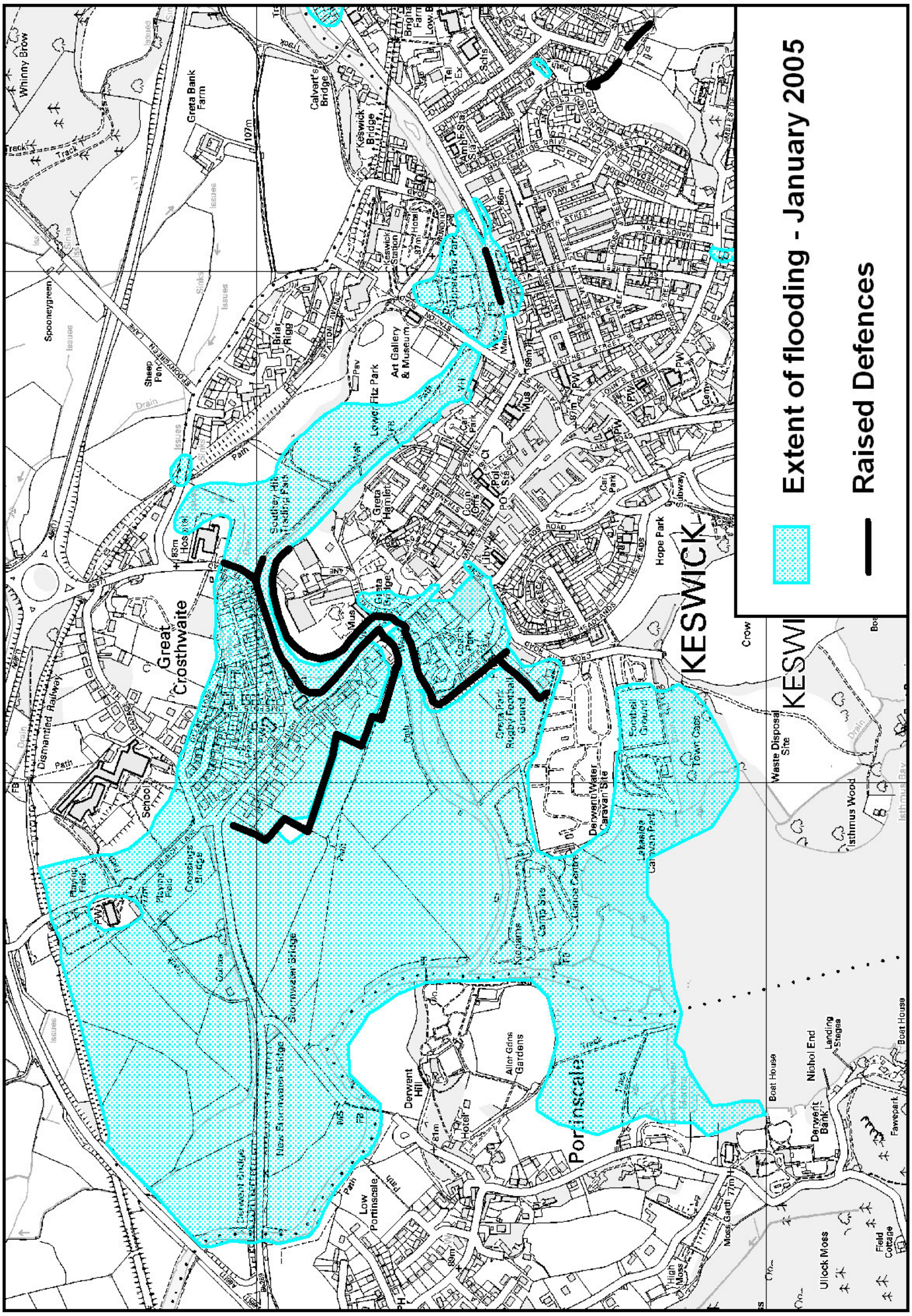
Allerdale Borough Council staff were in Keswick from approximately 1900hrs on 7 January to provide sandbags to householders. Cumbria Fire and Rescue Service, Keswick Police and Keswick mountain rescue team rescued and evacuated people from 0000hrs on 8 January.

Approximately 185 residential properties and 13 businesses were flooded in the town. Many roads were impassable including Penrith Road Main Street and Tithebarn Street.

Due to the 90mph winds and the substations which flooded, power to many areas was cut off for up to 2 days. This also resulted in mobile phone networks being out of action.

The sewage pumping station stopped working at approximately 2200hrs on 7 January.

Figure 6-5: Flood outline in Keswick



6.2.5 Maryport

No. of properties affected: 1 Cause of flooding: River Ellen and overland flows Key Points: • This section of the Ellen is largely tidal • The allotments along Selby Terrace flooded

Maryport lies on a largely tidal section of the River Ellen and the land along the river is very flat in places.

The river was inspected just below Mote Hill, near the outfall, and no definite upstream wrack marks could be located, possibly because this section of the river is largely tidal.

The high level of the downstream wrack marks suggest they were from the flood event and were unaffected by the tides. The first of these was behind the car park of the Co-op store, just downstream of the A596 Curzon Street Bridge.

Upstream of the bridge, no clear wrack marks could be found, although mud and silt deposits on top of the left bank wall, which is in poor condition, show that the river overtopped the wall.

Upstream of the Station Street Bridge, there is a wall on the left bank from the fire station to the A594. There was wrack all the way alongside the base of the wall but it was not clear if water had risen up the wall.

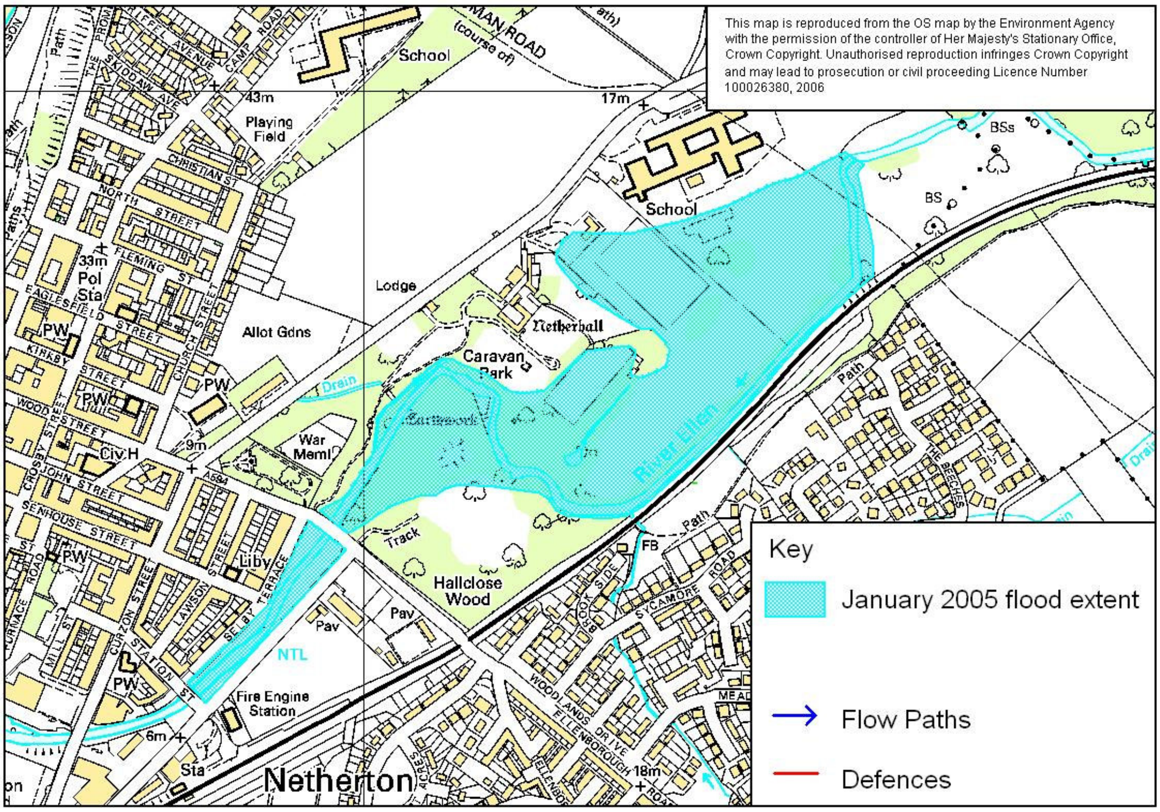
Various sources reported that the allotments at Selby Terrace flooded.

Photograph 6-7: Netherhall Rugby Club flooded

(Source: bbc.co.uk/cumbria – taken by Stephen Thompson)

A member of the public informed us the Rugby Club flooded, which has since been confirmed. Wrack marks show that water covered most of the car park and so it appears likely that the club did flood. Practically all of the sports fields were under water during the event and there were wrack marks along the fence at Netherhall School.

Figure 6-6: Flood outline in Maryport



6.2.6 Millhouse

No. of properties affected: 4 Cause of flooding: River Caldew, Gillcambon Beck and surface water Key Points: • The defences upstream of the bridge appear not to have been overtopped • The defences downstream of the bridge, which are in poor condition, were overtopped along their full length • Flooding to three houses was caused by road and land runoff, not the river

Millhouse lies downstream of the confluence of the River Caldew and Gillcambon Beck. There are defences on the right bank upstream of the bridge and on the left bank downstream of the bridge. The latter, which are in poor condition, were overtopped.

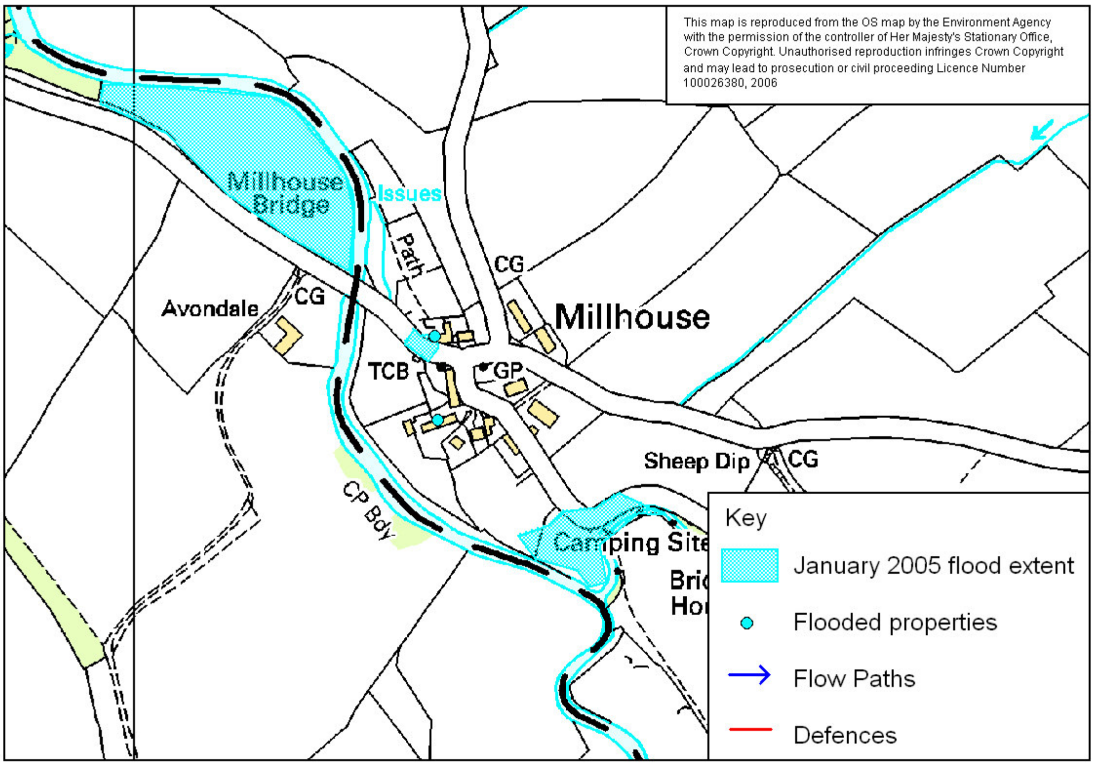
Flood waters rose to part way up the lawn of the bungalow on the right bank, upstream of the bridge. The highest wrack mark on the defences was approximately 0.75m below the crest.

The touring caravan park and campsite were covered by water to a depth of approximately 300mm. Both watercourses were out of bank and the footbridge on Gillcambon Beck was surcharged by approximately 300mm.

The converted mill and two terraced cottages on the right bank upstream of the bridge flooded. The flooding was from road and land runoff, which was unable to enter the river.

Photograph 6-8: River Caldew overtopping river bank at Millhouse

Figure 6-7: Flood outline in Millhouse



6.2.7 Rosthwaite, Borrowdale

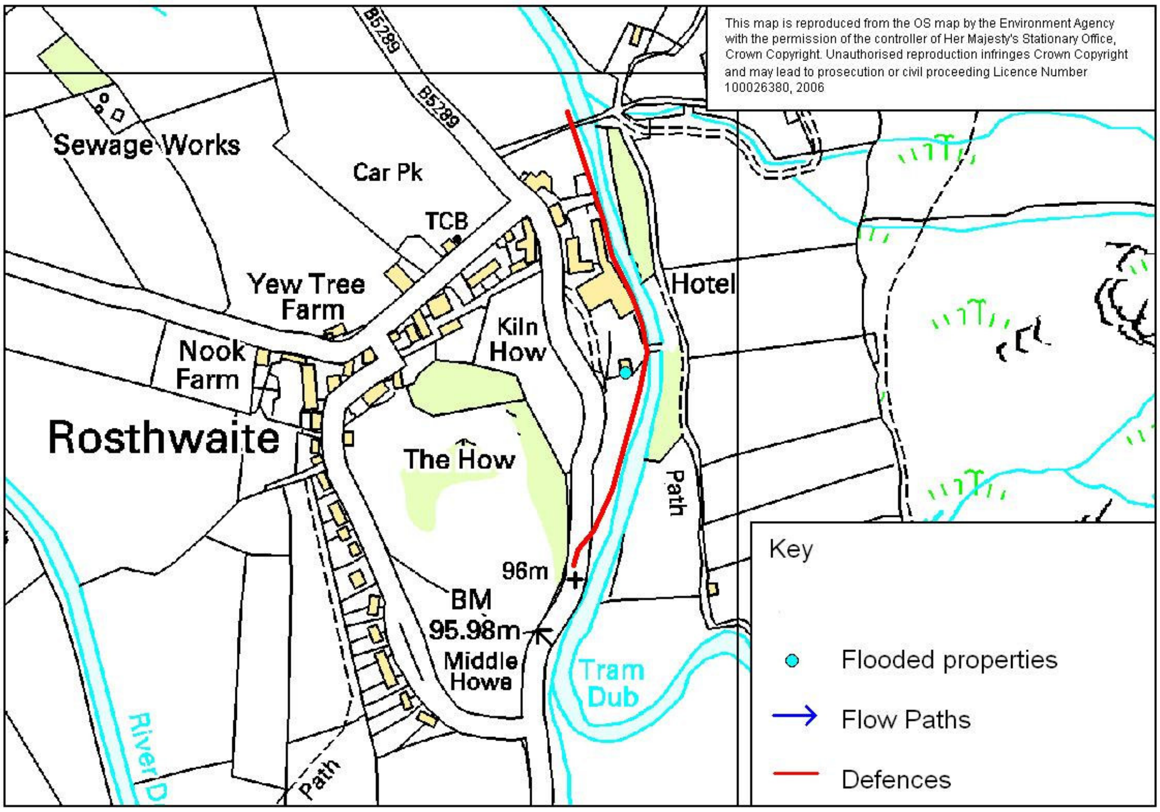
No. of properties affected: unknown Cause of flooding: Groundwater Key Points: • No defences were overtopped

Rosthwaite lies in the flat valley between the River Derwent and Stonethwaite Beck. The flood defences along the left bank of Stonethwaite Beck were not overtopped during the event.

A wrack mark some 0.6m below the crest level of the embankment was evident in Scafell car park. Downstream of the village, the flow was not out of channel and did not reach the toe of the 0.75m high embankment.

It is possible that any flooding of properties in Rosthwaite was caused by high groundwater levels in the gravels.

Figure 6-8: Flood outline in Rosthwaite



6.2.8 Wigton

No. of properties affected: 22 Cause of flooding: Wiza Beck and Speet Gill Key Points: • In the Speet Gill area, the road bridge and footbridge restrict flows • Road bridges with limited capacity also caused the river to back up and come out of bank in the Wiza Beck area

Wigton is situated between Wiza Beck and Speet Gill. The two watercourses have a history of flooding, with the most recent events being January 2000 and January 2004. There are no flood defences.

6.2.8.1 Speet Gill Area

The road bridge has limited capacity, which causes flows to come out of channel and flood nearby properties. The upstream footbridge also restricts flows, which exacerbates the problem. Downstream of the road bridge, the river was out of channel but no properties flooded. Three commercial properties, including the retained service fire station, one school and four houses were flooded in this area.

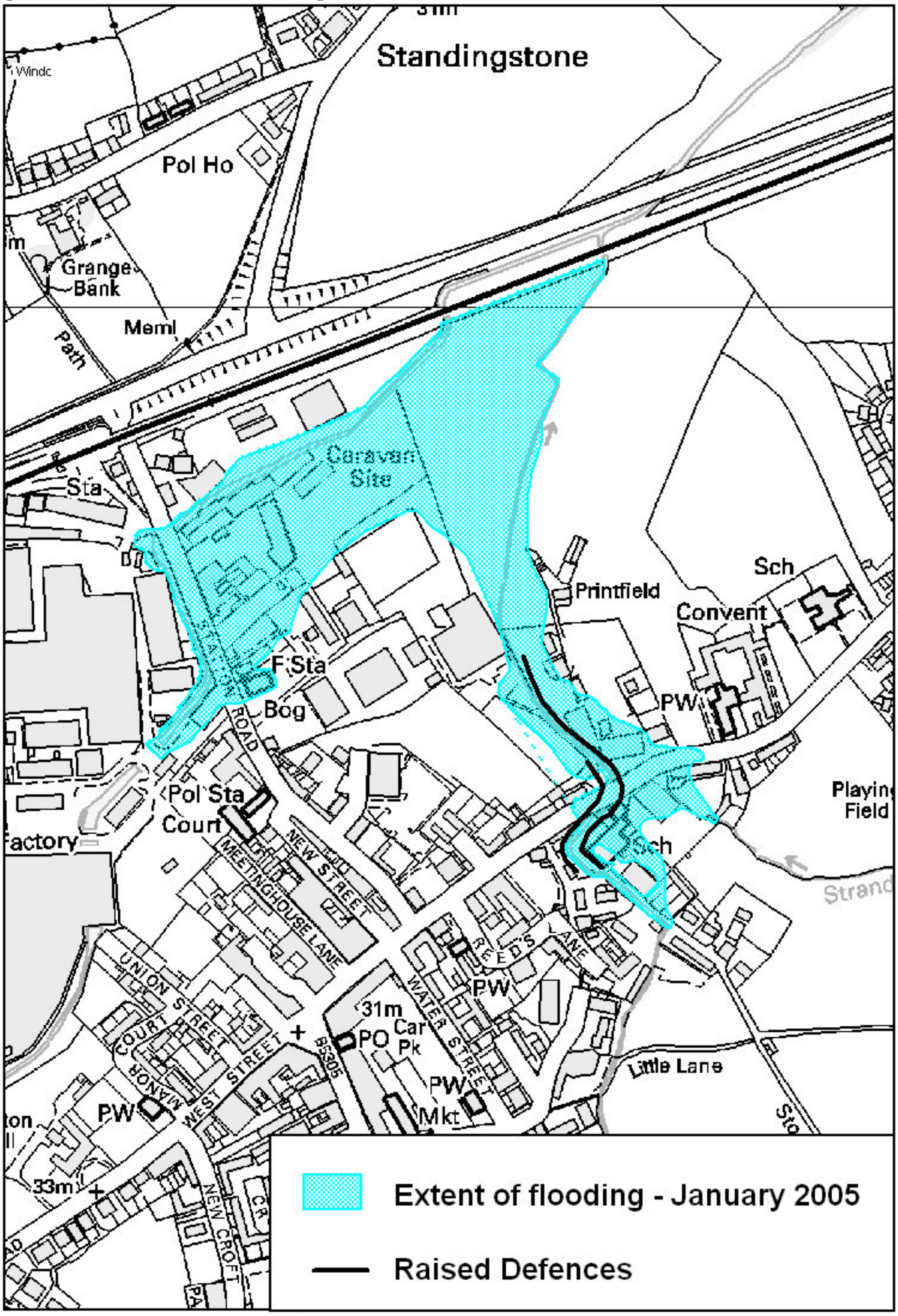
6.2.8.2 Wiza Beck Area

Photograph 6-9: Damage to the bank of Wiza Beck

The river first came out of the channel at a recently constructed bridge at the entrance to a factory; flows ran down the highway and onto Station Road. Subsequently, the river bank along Station Road was overtopped by up to 75mm along its 125m length. Water flowed through the industrial estate and back into both Wiza Beck and Speet Gill. The depth of flooding was comparatively shallow at some 300mm. The highway bridge, which is on a 90 degree bend with limited capacity, is the main problem in this area. Ten properties, three houses and a residential caravan site flooded.

Allerdale Borough Council had contractors on site to provide residents and businesses with sandbags. The police closed roads at both locations but these were reopened the following day.

Figure 6-9: Flood outline in Wigton



6.3 <u>Carlisle City</u>

6.3.1 Carlisle

No. of properties affected: 1865 Cause of flooding: Rivers Petteril, Caldew, Eden and Little Caldew; surface water; ground water Key Points: • The **Warwick Road** area has some protection • Two elderly residents drowned in their homes in Warwick Road • A total of 1147 properties flooded in the Warwick Road and Harraby Green areas • Work was already in progress on improvements to the defences in the Warwick Road area • **Willow Holme** is at the confluence of the Rivers Caldew and Eden, and flooding occurred from both rivers • The area is protected by flood defences along the River Caldew • The police, fire & rescue services and Carlisle City Council properties in Rickergate flooded and had to be temporarily relocated • A total of 635 properties flooded in this area • The embankments which protect **Low Crosby** from the River Eden breached in a number of places • A total of 83 properties flooded in the Low Crosby to Warwick Bridge area

Carlisle lies at the confluence of the Rivers Eden, Caldew and Petteril.

High winds resulted in the loss of the electricity supply at 05.00hrs on 7 January with the subsequent loss of landline phones and mobile networks.

6.3.1.1 Warwick Road Area

The Warwick Road area has some protection from the embankments on the Eden/Petteril, which were constructed in the early 1970s.

The Flood Warning for Warwick Road was issued at 0314hrs on 8 January. Flooding in the Greystone Road area began at 0250hrs and the Petteril outflanked its defences at 0251hrs. Overtopping of the embankments began around 0830hrs on 8 January. A Severe Flood Warning was, therefore, issued for this area at 1045hrs. The Flood Warning was issued six hours before the criteria were met but flooding from surface water, groundwater and the Petteril had already commenced.

Both the footbridge and Botcherby Bridge were blocked by fallen trees during the event. The River Eden started to overtop its defences at approximately 0830hrs.

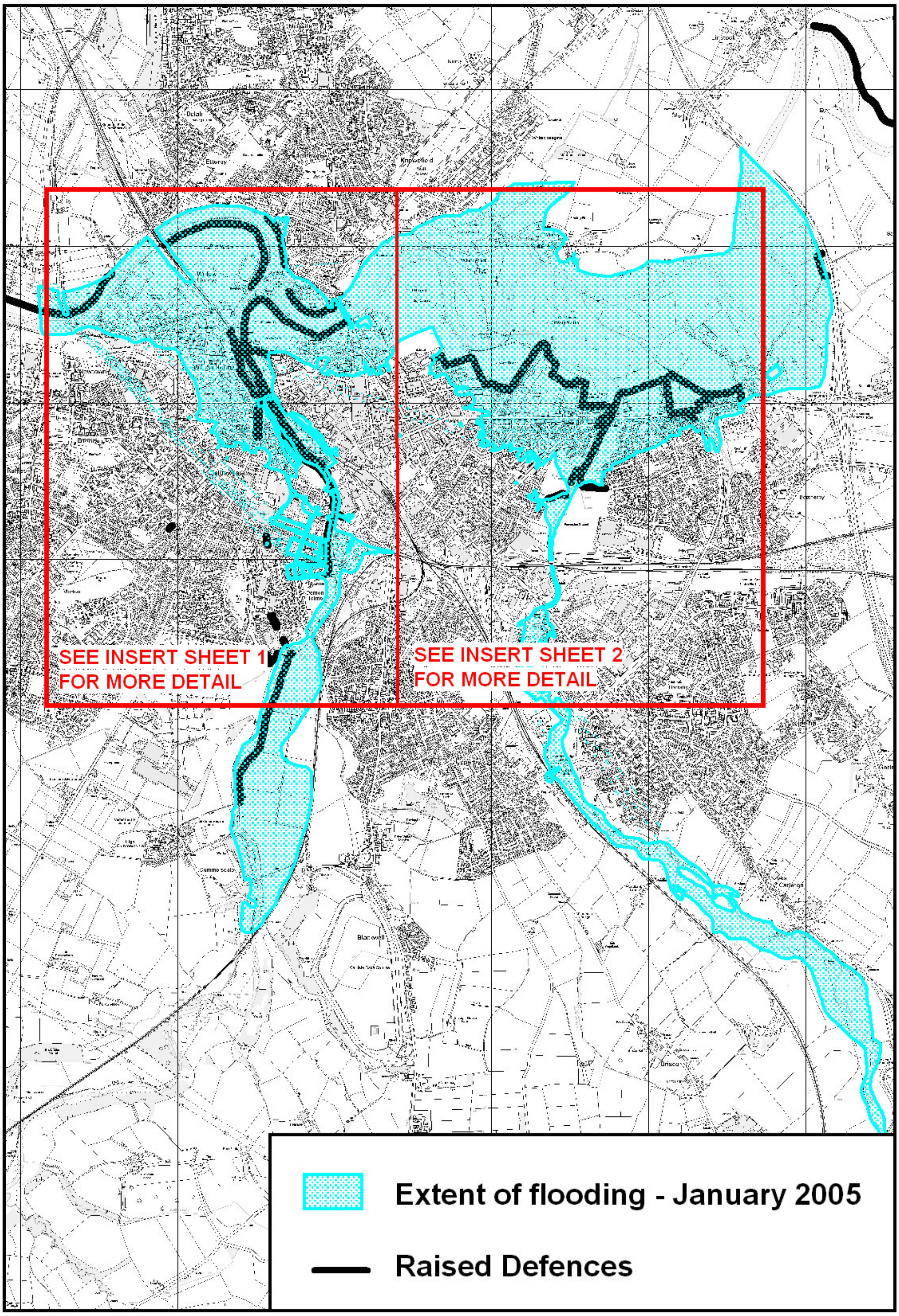
The embankments in the Warwick Road area were overtopped by approximately 0.7m. The depth of flooding in Warwick Road was 1.5m with some isolated spots of almost 2m.

Unfortunately two residents in adjoining properties on Warwick Road died during the event. Both properties had been offered the AVM flood warning service but neither had taken up the offer.

The Environment Agency’s workforce were present on site throughout the event. The numbers were limited due to the adverse weather conditions.

Local contractors assisted with plant and labour to make three controlled breaches in the flood banks on 9 January, and to repair the breaches during the next few days.

Figure 6-10: Overview of Flooding in Carlisle



The police, fire and rescue and City Council workers were present throughout the event.

Prior to this flooding, work was in progress on improvements to the defences and construction began in May 2006.

1126 residential and commercial properties were flooded in the Warwick Road area and a further 21 were flooded by the River Petteril.

Figure 6-11: Flood outline 1 in Carlisle

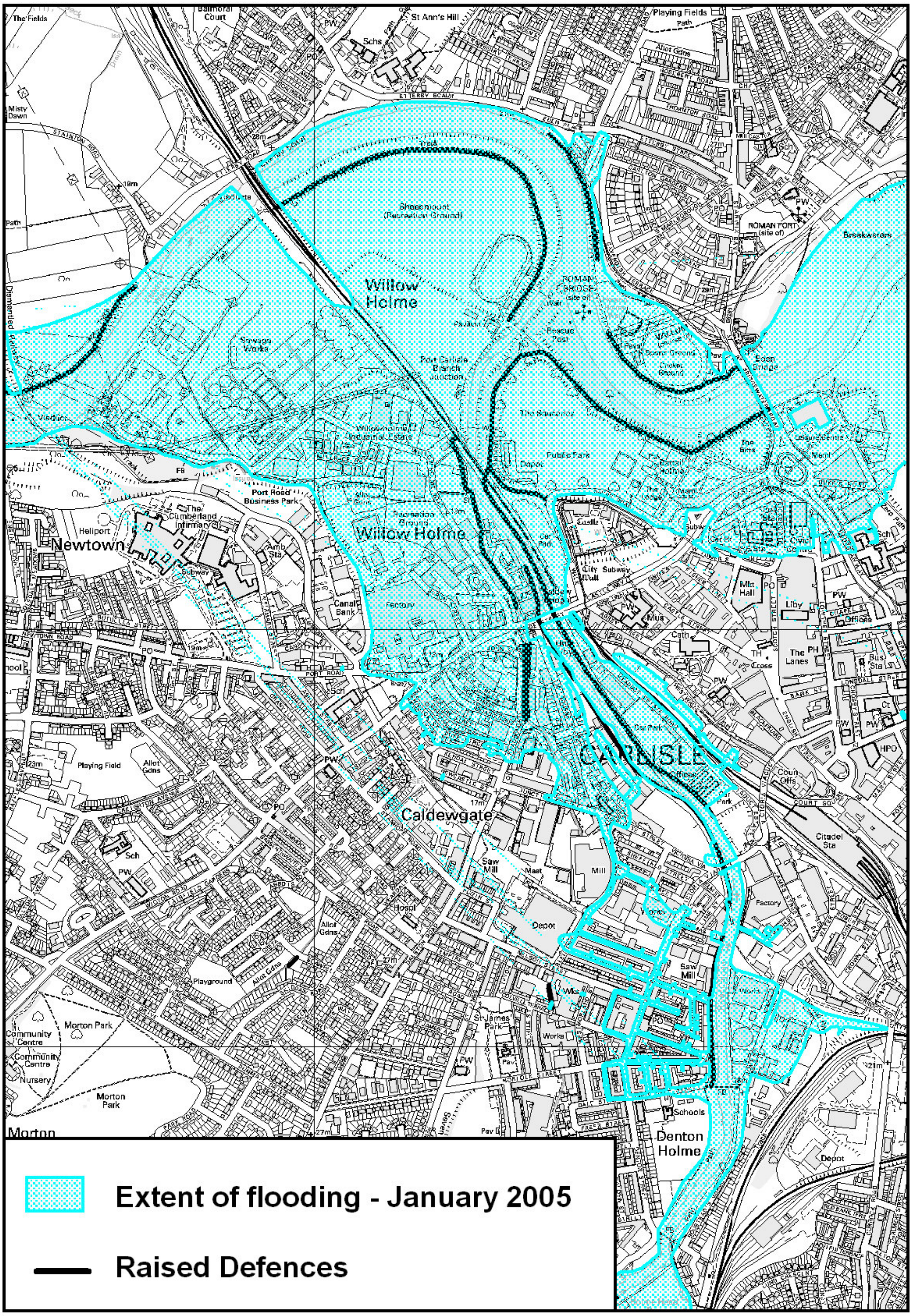
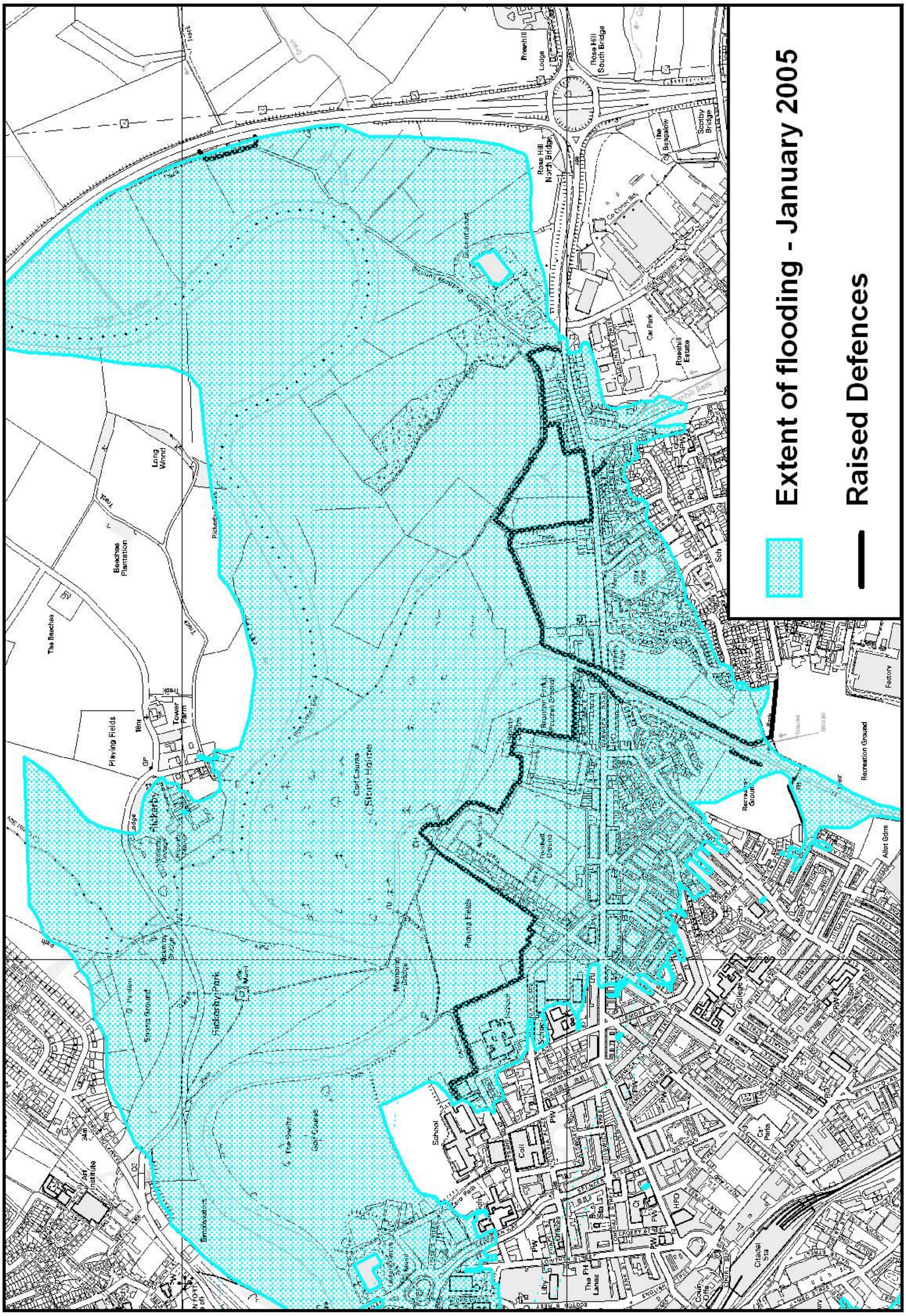


Figure 6-12: Flood outline 2 in Carlisle



Denton Holme, Willow Holme and City Centre

Photograph 6-10: Flooding on Irishgate on 8 January 2005

There are flood defences along the Caldew, which were constructed following the flooding in 1963 and 1984. The estimated standard of protection is 1 in 50 years.

Willow Holme is at the confluence of the Rivers Caldew and Eden, and flooding occurred from both rivers. High river levels in the Eden have an effect on the River Caldew. The floodplains of both rivers merge just downstream of Eden Bridge.

Denton Holme is affected by flows from the River Caldew. A now disused millrace, the Little Caldew, also flows through this area and contributes to the flooding. A number of COWs add to the problem.

The Willow Holme, Denton Holme and city centre areas are covered by separate flood warning areas. Flood Warnings were issued at 0502hrs, 0048hrs and 0222hrs on 8 January for the city centre, Etterby Terrace and Denton Holme respectively. At 1044hrs that day, this was increased to a Severe Flood Warning for Denton Holme and the city centre.

Denton Holme

The flooding mechanisms in this area are very complex and factors include numerous COWs, the Little Caldew, backing up of the Caldew from the Eden and the Rivers Eden and Caldew themselves. During this event, the combined foul and surface water sewers were gravity locked by the Eden. This prevented flows discharging from the treatment works and caused surcharging in the sewers.

Photograph 6-11: Flooding on Caldewgate on 8 January 2005

Key emergency and public services in Rickergate flooded and relocated to temporary offices around the city.

The initial flooding occurred shortly after 0200hrs and was witnessed by the Environment Agency's Hydrometry staff. Trees became lodged on the South Vale footbridge and forced flows onto East Dale Street, on the left bank of the Caldew. These flows were conveyed to the low lying areas of Denton Street and entered the Little Caldew (millrace) and Willow Holme.

Flooding occurred to the gasworks area on the right bank at the same time, when the defences were overtopped and a wall collapsed. The defences on the left bank from South Vale footbridge to Victoria Viaduct were not overtopped.

Downstream of Victoria Viaduct to Caldew Bridge, the defences on the right bank were overtopped and commercial and residential properties flooded. There is a flow route from this area to the Eden and flows from both rivers eventually merged. Evidence from CCTV suggests that the initial flooding to the right bank was from surcharging of the surface water system. The Shadongate area is low lying and it received flows from the Caldew via the Little Caldew; it flooded to a depth of some 1.8m. The defences to the left bank were overtopped to a very limited extent, directly downstream of Victoria Viaduct; no properties flooded and the affected area was very small. This flooding occurred between 0230hrs to 0430hrs.

Photograph 6-12: Flooding at Rickergate on 8 January 2005

(Source: bbc.co.uk/cumbria – taken by Daniel Mason)

A second phase of flooding occurred to the lower areas of the Caldew at 1100hrs and is likely to have been caused by backing up from the Eden.

317 properties flooded in the Denton Holme area. This is less than the first estimates as follow up work demonstrated that, although some roads flooded to a depth of 300mm, property thresholds are higher. Flood waters were conveyed to the low lying areas.

Willow Holme and The Sauceries

The first reports of flooding in Willow Holme were received at 2230hrs on 7 January and related to surcharge of the sewers/highway drains. The area has a history of this type of flooding and the sewage treatment works cannot discharge against 1 in 5 water levels in the River Eden. Site controllers were present at 2240hrs and witnessed the sewers surcharging; there was no river flooding at this time.

The situation continued to worsen and by 0030hrs the site controller requested pumps to pump the Little Caldew over the sluices at the Maltings. This is a normal operational response as the Little Caldew becomes gravity locked. The pumps were in place by 0130hrs.

The first peak on the Caldew occurred at 0200hrs. This resulted in flooding from the Little Caldew, which conveyed flows from the Caldew, and the Caldew, which overtopped its defences below Caldew Bridge on both banks. These flows, in combination with flows from the sewers and surface water, inundated the Willow Holme area. Large volumes of water were conveyed through the area towards the sewage treatment works and main substation. As a result of this the main substation, had a power failure at 0500hrs. This affected some areas of Carlisle and several surrounding areas.

Dow Beck, a small urban main river, joins the Little Caldew at the Maltings and this added to the problem. Operational staff attempted to warn residents at the Maltings of flooding.

The railway bridge downstream of Caldew Bridge lacks hydraulic capacity and flows back up.

The Caldew flooded again at 1100hrs on 8 January due to rising water levels in the River Eden. This caused flows to back up the Caldew and overtop the defences a second time. This increased the flooding in Willow Holme but by this time the properties were evacuated.

221 properties flooded in the Willow Holme area, including the bus depot, the Maltings and student accommodation for the university, many businesses and the United Utilities' power substation and sewage treatment works.

City Centre

Photograph 6-13: Flooding at Hardwicke Castle on 8 January 2005

The area around the Civic Centre and Hardwick Circus was just included in the Flood Zones as a result of recent modelling. The AVM take-up was very low. Of the 66 properties which flooded, only three took up the offer.

Anecdotal evidence suggests that the initial flooding was caused by surcharge of the sewers, after the power failure from 0600hrs to 0830hrs. The principal cause was flows from the Eden and water bypassed Eden Bridge and flooded the underpasses into the city centre between 0930hrs and 1100hrs. Flows also overtopped the embankments downstream of Eden Bridge at the same time. The depth of flooding was 2m in places.

66 properties flooded including many businesses, the police station, fire and rescue station and Civic Centre.

Etterby Terrace

Etterby Terrace is on the right bank of the River Eden, just downstream of the confluence of the Rivers Caldew and Eden. There are no defences.

31 properties in Rickerby and Etterby Terrace flooded; these are on the right bank of the River Eden.

A final total of 635 properties flooded in Willow Holme, Denton Holme and the city centre.

Many roads in the city remained closed until 10 January including the A595, the main route into Carlisle from the south west.

The main substation at Willow Holme was flooded. The emergency services tried to obtain access to it to facilitate repairs but the depth of water on the approach road prevented this until 10 January. The sewage treatment works in Willow Holme relies on pumped flows and the power failure hampered efforts to reach the substation.

The West Coast Main Line was damaged just upstream of the River Eden bridge crossing, at the point where the embankment was damaged. Network Rail carried out emergency repairs and the line was opened on 17 January.

Staff from the Environment Agency were on site throughout the event. The emergency services, including mountain rescue and Carlisle City Council, helped evacuate the area. Emergency pumping units, recently purchased by Central Government, were deployed in the city.

6.3.1.2 Low Crosby to Warwick Bridge

Photograph 6-14: Flooding at Warwick Bridge

(Source: bbc.co.uk/cumbria – taken by Robert Reed)

The Eden Valley Flood Warning Area includes low lying land and properties/roads in Crosby-on-Eden and Warwick Bridge. It only covers 18 properties but includes large areas of agricultural land.

The Flood Warning was issued at 1832hrs on 7 January. Flooding started in Low Crosby at 0530hrs the following day.

Low Crosby has embankments to protect it from the Eden; they were constructed in the 1950s. During this event, the embankments on both sides breached in several places.

The flooding was initially caused by surcharging of the surface water drains. Willow Beck, which runs through the village, also contributed to the problem. Flooding from the river started at approximately 0530hrs on 8 January.

Some properties between Low Crosby and Warwick Bridge flooded as a result of the breaching of the embankments.

In Low Crosby and the surrounding area, a total of 44 properties flooded and a further 10 flooded between Low Crosby and Warwick Bridge. At Warwick Bridge, approximately 29 properties were flooded, including 16 apartments recently converted at Holme Eden Abbey.

A total of 83 properties flooded in the Low Crosby to Warwick Bridge area.

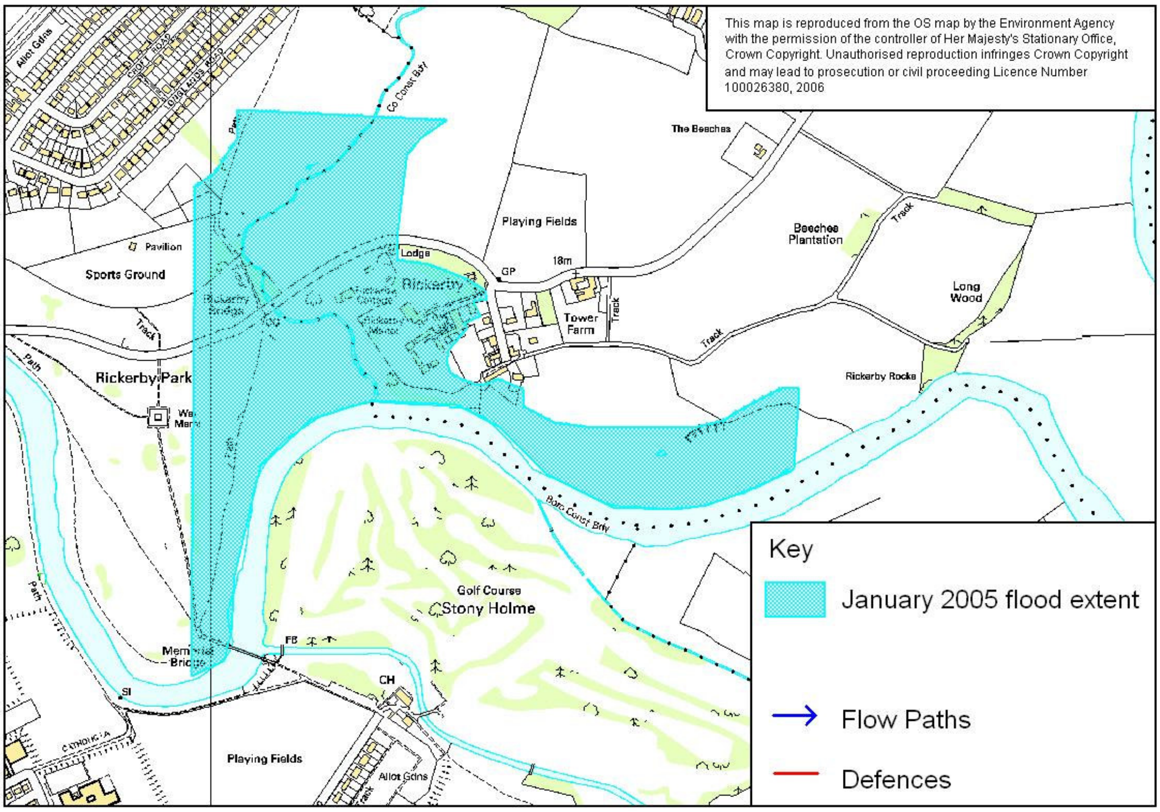
Because of the flooding in Carlisle and the other urban areas, no Environment Agency personnel were on site during the event.

Police, fire and rescue and City Council staff were present during the event.

6.3.2 Rickerby

No. of properties affected: 14 Cause of flooding: River Eden Key Points: • The Eden overtopped the right bank upstream of the confluence with the Petteril

Figure 6-13: Flood outline in Rickerby



Flooding only shown on north bank close to the village (see also the main Carlisle plan Figure 6-12).

6.3.3 Roe Beck

No. of properties affected: 17 Cause of flooding: River Roe and overland flow Key Points: • There are no raised defences along the Roe • The new development at Thistlewood flooded • The low level of the bridge soffit restricts the flow

Roe Beck is a small tributary of the River Caldew. It runs north for approximately 15km from Skelton and Ivegill to its confluence with the Caldew, approximately 750m downstream of Gaitsgill. Just under half of its length is main river. The area is characterised by steeply incised and often tree lined valleys in gently rolling terrain dominated by agricultural land. Along its middle reaches, the narrow valley floor is dotted with properties and small developments, many of which are converted farm buildings and mills.

There are no raised defences on Roe Beck and there is a limited history of flooding.

According to the locals, the peak in the river occurred at around 0200hrs on 8 January. The new development at Ivegill (The Grange) had some flooding to a garage. Rose Cottage and Ghyll Side had wrack marks in the gardens.

The Beckfoot Farm development at Thistlewood, immediately upstream of the confluence of the River Ive and Roe Beck, was under construction and flooded. Robin House at the confluence did not flood.

Photograph 6-15: Bridge in Cockermouth beginning to restrict flow

(Source: bbc.co.uk/cumbria – taken by Zara)

According to nearby residents, the main development site on the opposite side of the river began to flood at 2230hrs on 7 January. The onset of property flooding was at 0300hrs of 8 January. Flows came out of the right bank as a result of a build up of debris on the handrails of a low bridge. Water also flowed overland from the bridge leading to Robin House. Runoff from the land and lanes above the development flooded properties in the north west corner of the site. Flooding depths were substantial and up to 1m in places.

The cellar of Peel Tower flooded.

There are various outfalls into the river, none of which have headwalls or flaps. Various trees lodged on the bridges and elsewhere; these have since been removed.

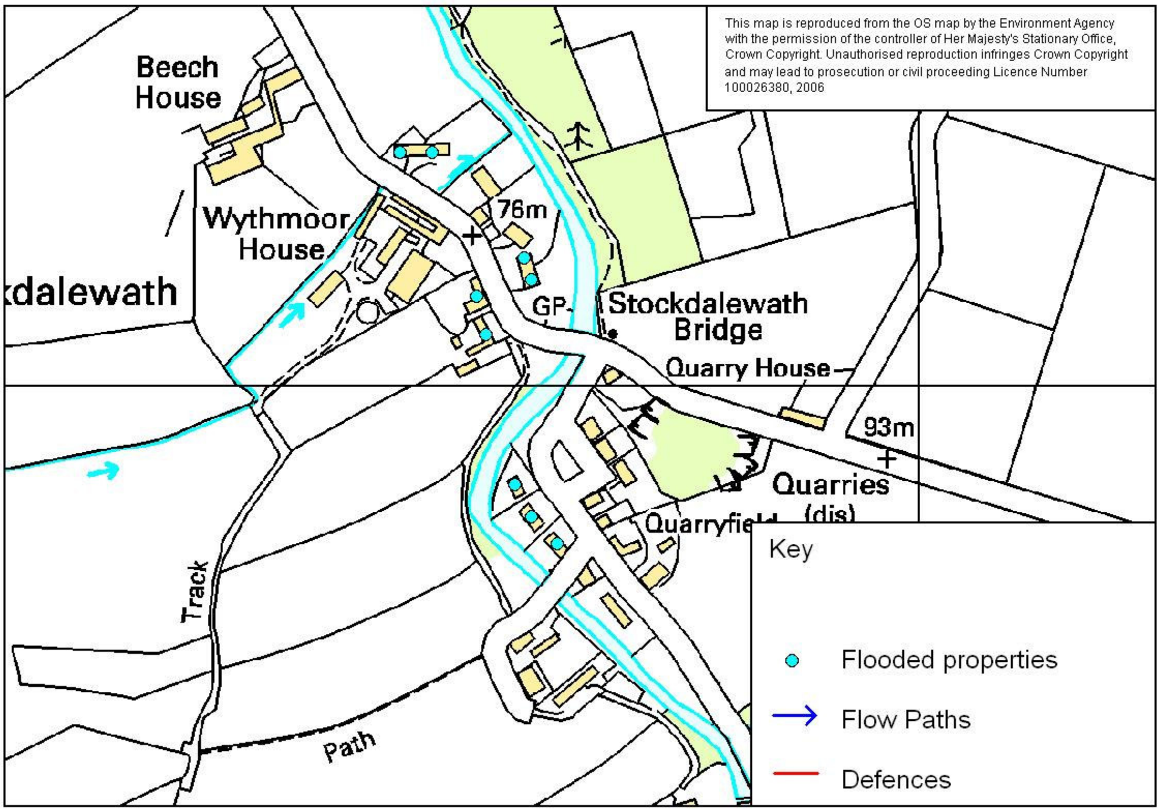
6.3.4 Stockdalewath

No. of properties affected: 12 Cause of flooding: River Roe Key Points: • The Roe burst its banks

Stockdalewath was significantly affected by flooding and a visit was made on 12 January to assess the extent.

The River Roe burst its banks and flooded approximately six houses in the village and a further three houses directly upstream. The river typically comes out of bank at the road bridge, which crosses the river in the middle of the village. From this point, water flowed northwards down the road and flooded further properties before re-entering the river.

Figure 6-14: Flood outline in Stockdalewath



Photograph 6-16: Wrack and debris left in the field on the left bank downstream of Stockdalewath Bridge

6.4 Eden District

6.4.1 Appleby

No. of properties affected: 53 Cause of flooding: River Eden, surface water system and small watercourse along Doomgate Key Points: • Chapel Street area evacuated • Defences not overtopped

The River Eden runs through Appleby. The majority of its defences, which were constructed in 1995 to a 1 in 100 year standard, were not overtopped.

Following the very heavy overnight rain, a team from the Environment Agency was sent to Appleby to raise the defences and shut the flood gates. This was done well before the flooding commenced.

Flood Warnings were issued at 1310hrs and 2156 hrs on 7 January.

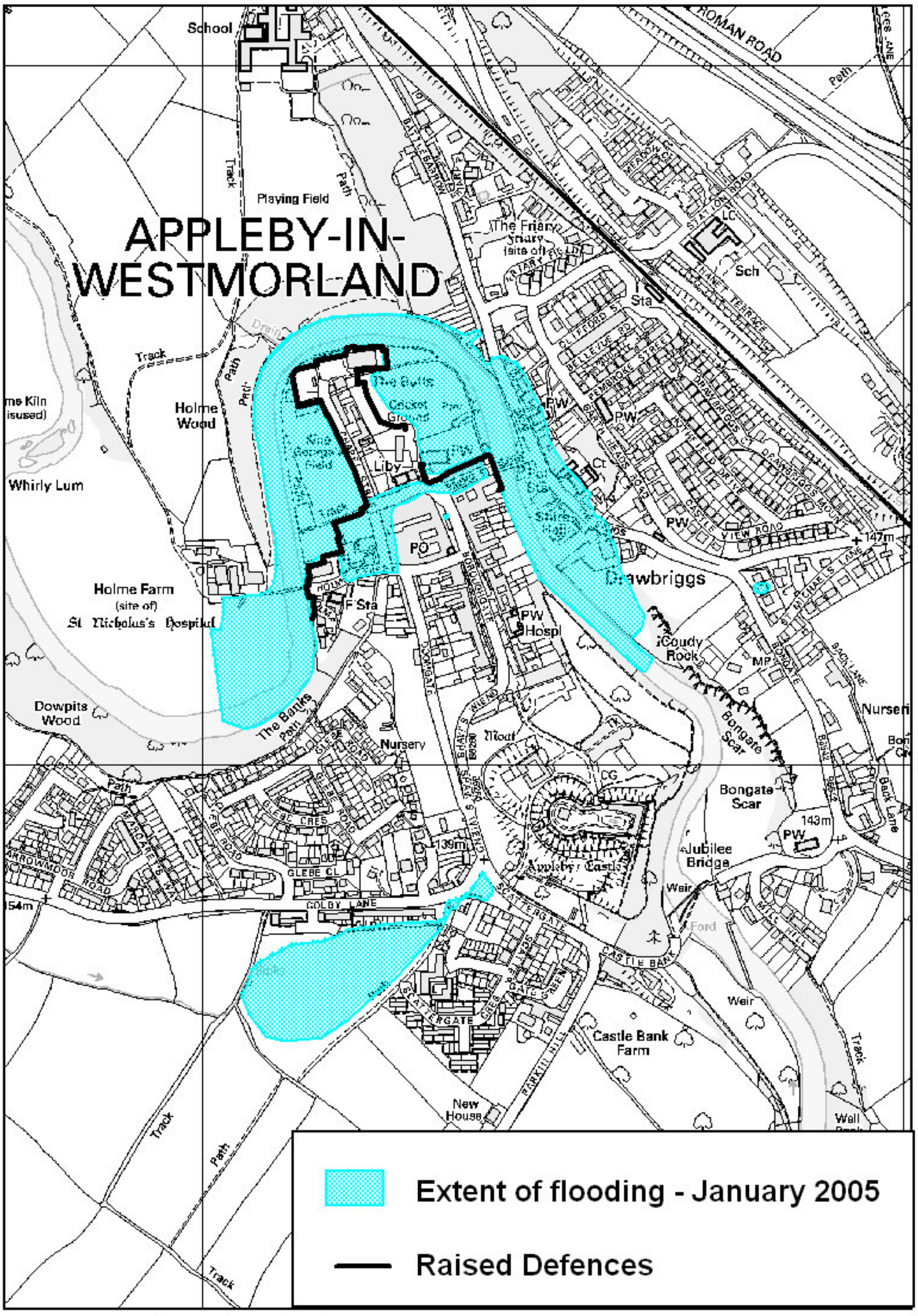
The River Eden started to flow out of bank between 1700hrs and 1800hrs, by which time the police and fire and rescue service were in position on Bridge Street, opposite The Sands. They undertook traffic control and helped with the sandbags.

Photograph 6-17: Flooding in Appleby

(Source: bbc.co.uk/cumbria – taken by Barbara Abbott)

The river continued to rise. Excess flows left the main channel in the bowling green area, passed along The Sands and returned to the channel downstream of the bridge. Properties along The Sands started to flood at 2100hrs. Within a couple of hours, The Sands was impassable and was under a depth of water of 1.2m. Water levels reached a peak at 0415hrs on 8 January.

Figure 6-15: Flood outline in Appleby



Flooding in the defended areas of Chapel Street, Bridge Street and Holme Street began around midnight. This was due to a combination of factors including surcharging of the surface water system, flooding from the Critical Ordinary Watercourse along Doomgate and some minor overtopping/penetration of the defences.

The storm sewage overflow chamber at the corner of Holme Street and Chapel Street, forms a hydraulic connection between the COW and the sewer. The outfall from the COW to the River Eden can also surcharge.

In the early hours of the morning, following a forecast that the defences would be overtopped, a decision was taken by the police and fire and rescue services to evacuate the Chapel Street area. The river came within 100mm of overtopping the defences. One of the floodgates was opened at around 0900hrs on 8 January to release floodwaters trapped around Chapel Street. River water continued to flow along The Sands until 1200hrs on 8 January.

Members of the Environment Agency's Risk Management and Operations Delivery Teams were on site throughout the event.

Approximately 30 properties along The Sands flooded, and a further 20 flooded along Bridge Street, Chapel Street and Holme Street. The Doomgate COW was responsible for flooding of three properties on Colby Lane.

6.4.2 Armathwaite

No. of properties affected: 2
Cause of flooding: River Eden
Key Points:

- Two properties upstream of the road bridge flooded

Armathwaite Castle and Dry Beck Farm flooded from the River Eden.

Photograph 6-18: Armathwaite Castle on 8 January 2006

(Source: bbc.co.uk/cumbria)

6.4.3 Blencow

No. of properties affected: unknown Cause of flooding: Surface water Key Points: • Two properties came very close to being flooded • Residents reported that the River Petteril burst its banks and flooded a field

Great Blencow and Little Blencow are situated on the River Petteril just downstream of Greystoke, Cumbria.

No properties are known to have flooded during the event, although two were threatened.

The residents confirmed that properties to the east of Blencow Bridge, including the church, were unaffected. There may have been flooding in a shed near the bridge. They also report that the river burst its banks on the opposite side and came through a field. There are no properties at this location.

Properties in the middle of Great Blencow were sandbagged. These are at a much higher level and it appears that the threat was from surface water rather than the river.

The road to Newbiggin and Penrith was flooded during the event.

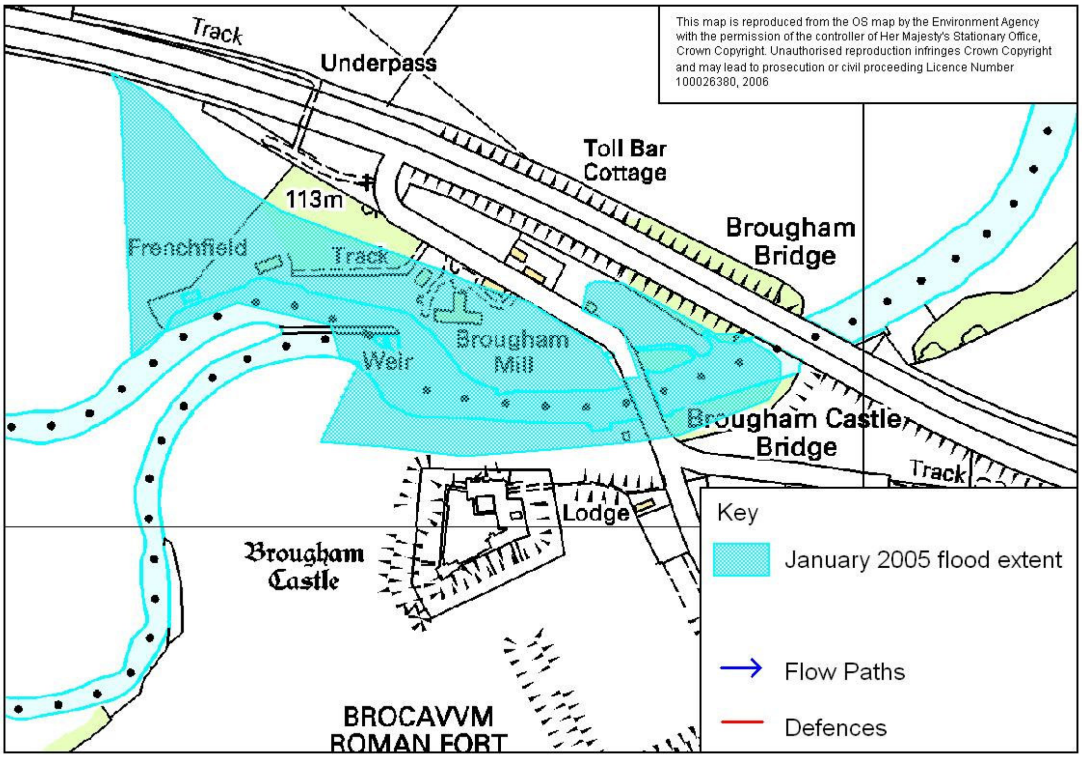
Photograph 6-19: Road flooding at Blencow Bridge

6.4.4 Brougham

No. of properties affected: 2 Cause of flooding: River Eamont Key Points: • The Frenchfield embankment was not overtopped

Photograph 6-20: Wrack marks in a field north of Frenchfield

Figure 6-16: Flood outline in Brougham



The embankment at Frenchfield appears not to have been overtopped.

All properties shown on the plan were surrounded by flood waters. There was internal flooding to at least one property at Brougham Mill and Frenchfield. The other units at Brougham Mill are some 750mm above ground and no internal flooding took place.

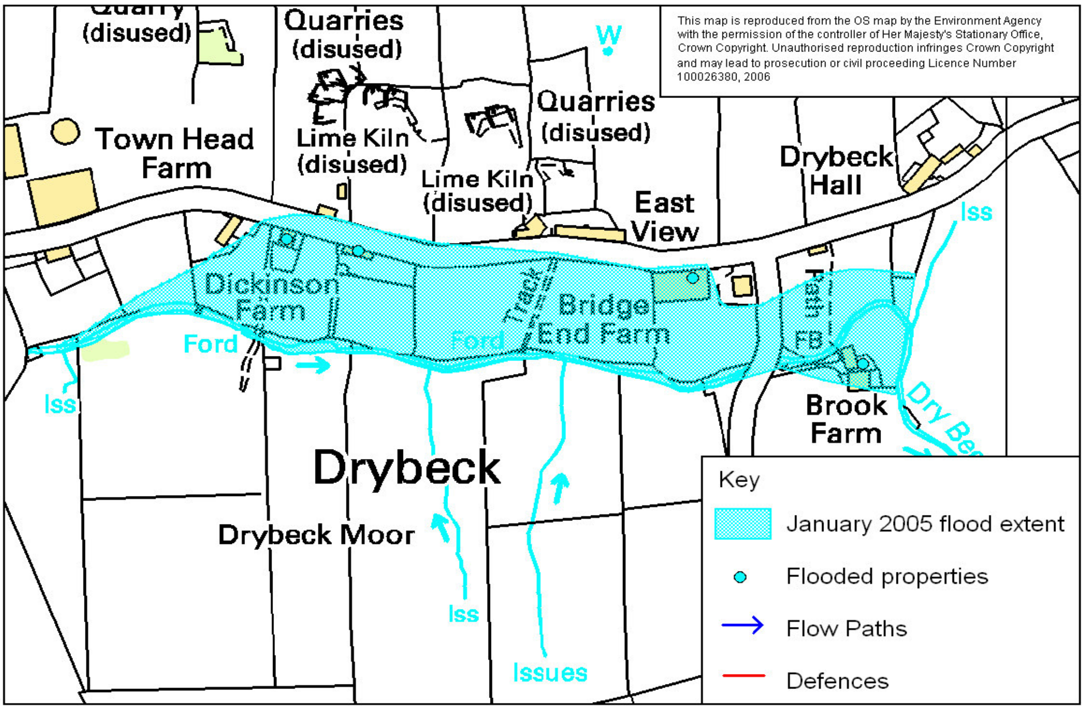
6.4.5 Drybeck

No. of properties affected: 4 Cause of flooding: Surface water, overland flow and Dry Beck

The flooding in Drybeck was as a result of surface water, overland flow and the river leaving its channel.

Four properties flooded namely Dickinsons Farm, Gobblety Cottage, Bridge End Farm and Brook Farm.

Figure 6-17: Flood outline in Drybeck



6.4.6 Eamont Bridge

No. of properties affected: 35 Cause of flooding: River Eamont, Ullswater Lake and Dacre Beck Key Points: • The triple arch stone bridge restricts flows

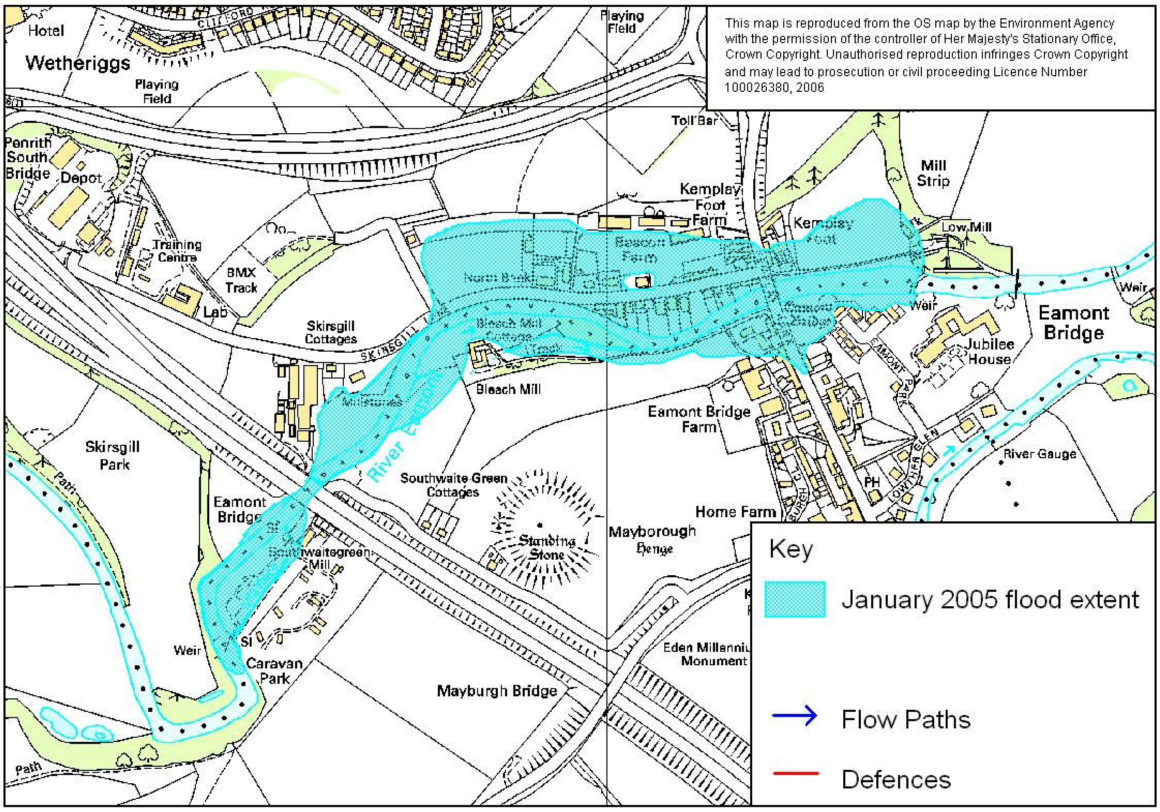
Water levels at Eamont Bridge are mainly influenced by the overflow from Ullswater Lake and flows from the tributary of Dacre Beck. There are currently no defences at Eamont Bridge.

A Flood Warning was issued at 2150hrs on 7 January.

Flooding occurred because the peak flow from Ullswater coincided with the peak from Dacre Beck. This was exacerbated by the afflux at a triple arch stone bridge. Flood waters spilt out of both banks at this point.

Reports suggest that the River Eamont burst its banks at Skirsgill Lane and formed flowpaths along Skirsgill Road and the rear of the properties on this road. The caravan park upstream of the M6 road bridge was also affected by flood water.

Figure 6-18: Flood outline in Eamont Bridge



Photograph 6-21: Eamont Bridge on the morning of 8 January

35 properties in Eamont Bridge were flooded during this event. The road was closed at Kemplay Bank.

Eden District Council were on site at 2006hrs on 7 January in response to requests for sandbags.

6.4.7 Maulds Meaburn

No. of properties affected: 3 Cause of flooding: Unknown

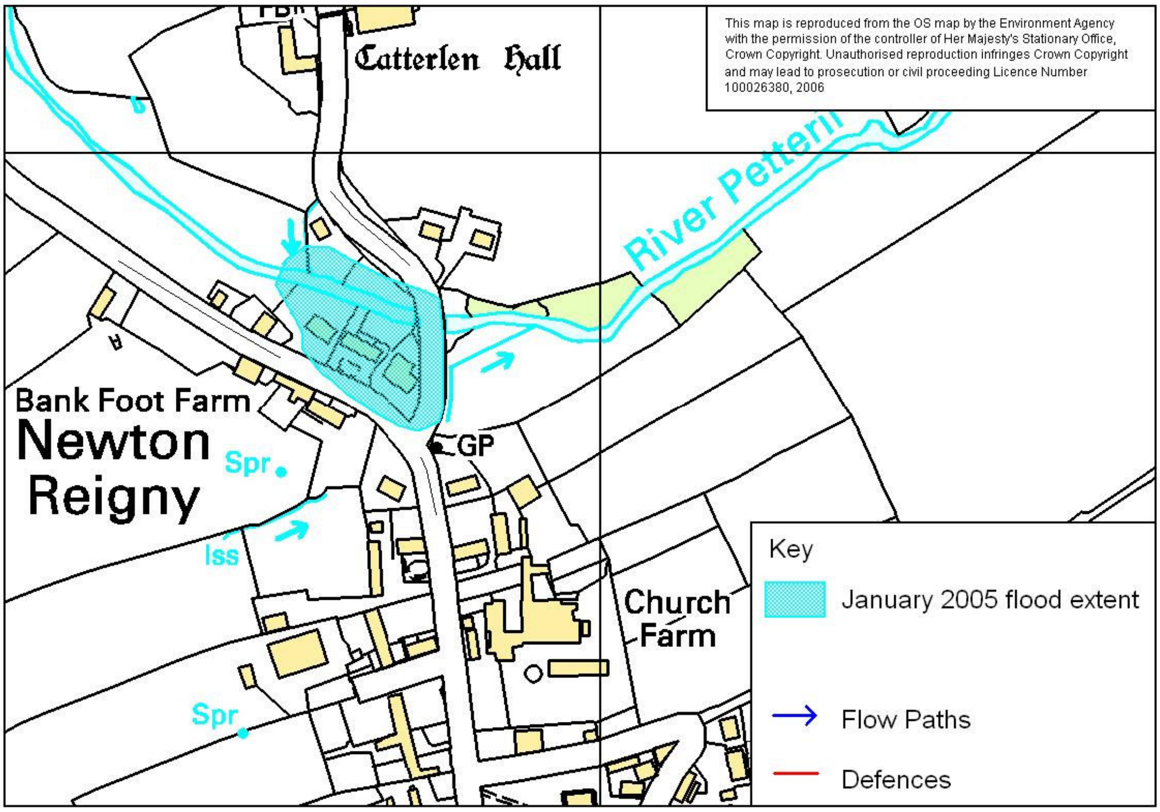
Three properties flooded internally to an approximate depth of 300mm. It is not known whether the converted barn flooded from the main river or a culvert.

6.4.8 Newton Reigny

No. of properties affected: 6 Cause of flooding: River Petteril and highway drainage Key Points: • The river overtopped the raised embankment

The pub flooded at midnight on 7 January, initially from highway drainage and flows backing up from the septic tank in its car park. It flooded to a depth of 400mm. The river overtopped the raised embankment at approximately 0200hrs on 8 January, reportedly only at the low point beside the septic tank. The landlord contacted United Utilities as there are no flaps on the outfall from the tank.

Figure 6-19: Flood outline in Newton Reigny



The terrace of houses next to the pub was sandbagged by the fire and rescue service. This prevented extensive internal flooding as the water level was 50mm above the floor level. The bungalow next to the terrace was similarly flooded with minimal internal damage.

The floodbank is thought to have been constructed by the residents.

Walls along the highway prevented surface water entering the river. The Highway Authority was contacted with a request to install extra gullies to drain to the downstream field.

One arch of the main road bridge was partially blocked by trees at the upstream end; this resulted in a build up of gravel in the channel.

6.4.9 Penrith

No. of properties affected: 21 Cause of flooding: Thacka Beck Key Points: • The heavy rainfall resulted in pockets of flooding

The watercourses of Thacka Beck, Myers Beck and Dog Beck have a history of flooding in Penrith. Much of Thacka Beck is culverted through the town. There are no flood defences.

Photograph 6-22: Penrith town centre

On this occasion, flooding only appears to have been from Thacka Beck. The areas affected were the rural floodplain and urban channel through the town centre.

The town centre was affected at four locations and a number of residential and commercial properties were flooded. The volume of water flowing through the culverts was sufficient to raise manhole covers and lift the tarmac.

Flooding to the Cumbria Police Headquarters at Carleton Hall was due to a combination of water from Thacka Beck and the River Eamont, which affected the lower lying units. The flooding of the police headquarters in Penrith meant that the communications room could not be accessed adding to the difficulties faced during the event.

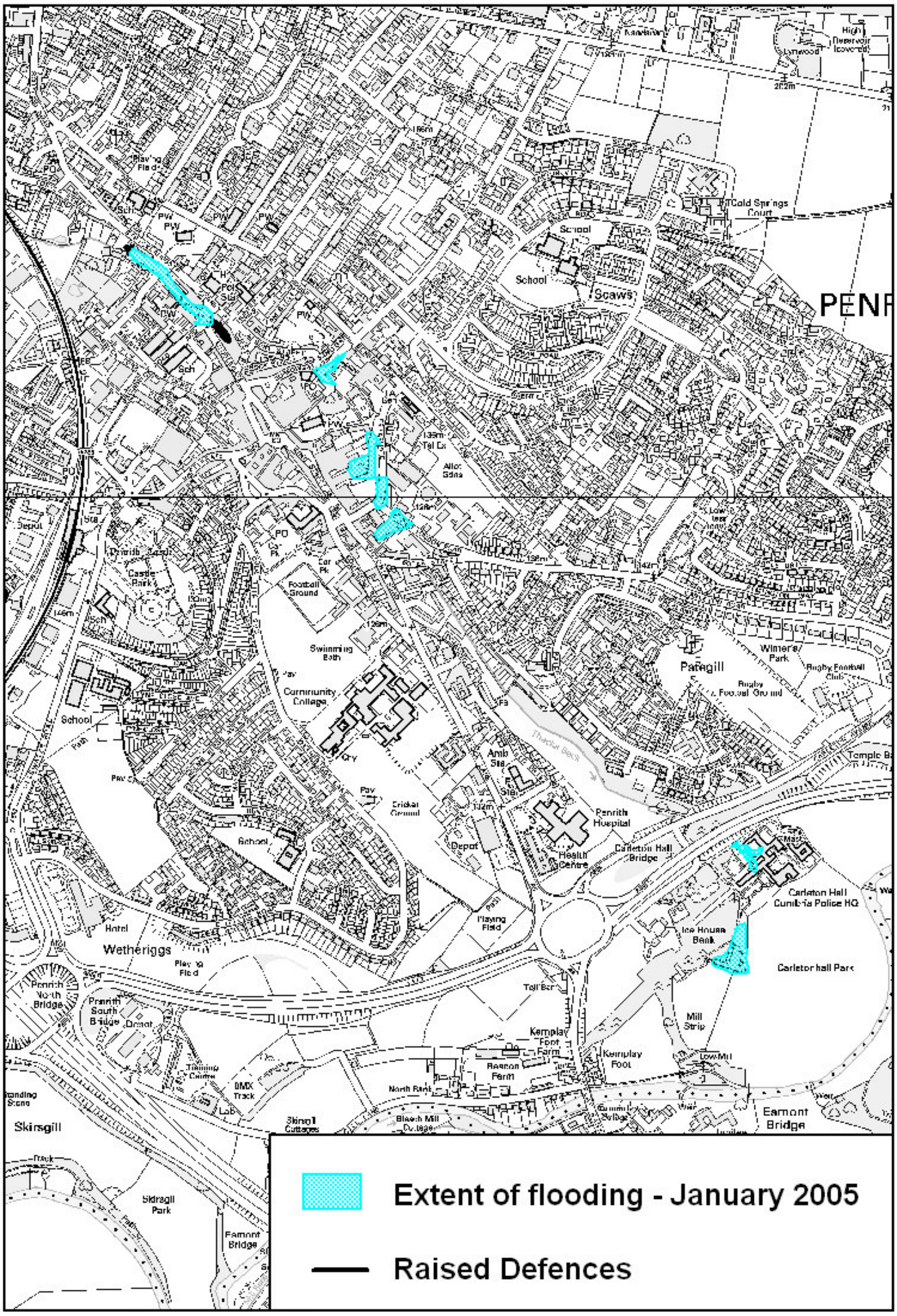
Initial flooding to Watson Terrace was attributed to a blockage of the trash screen on the culvert entrance. Other areas were flooded by the surcharging of access chambers on Thacka Beck.

Previous hydraulic and condition studies of Thacka Beck identified capacity and structural issues, which are currently the subject of a feasibility study.

16 residential properties and five commercial properties flooded during this event.

Operatives from the Environment Agency were on site to clear the trash screen at Watson Terrace. Temporary measures were taken to support the wall at the screen. Eden District Council were on site to provide sandbags.

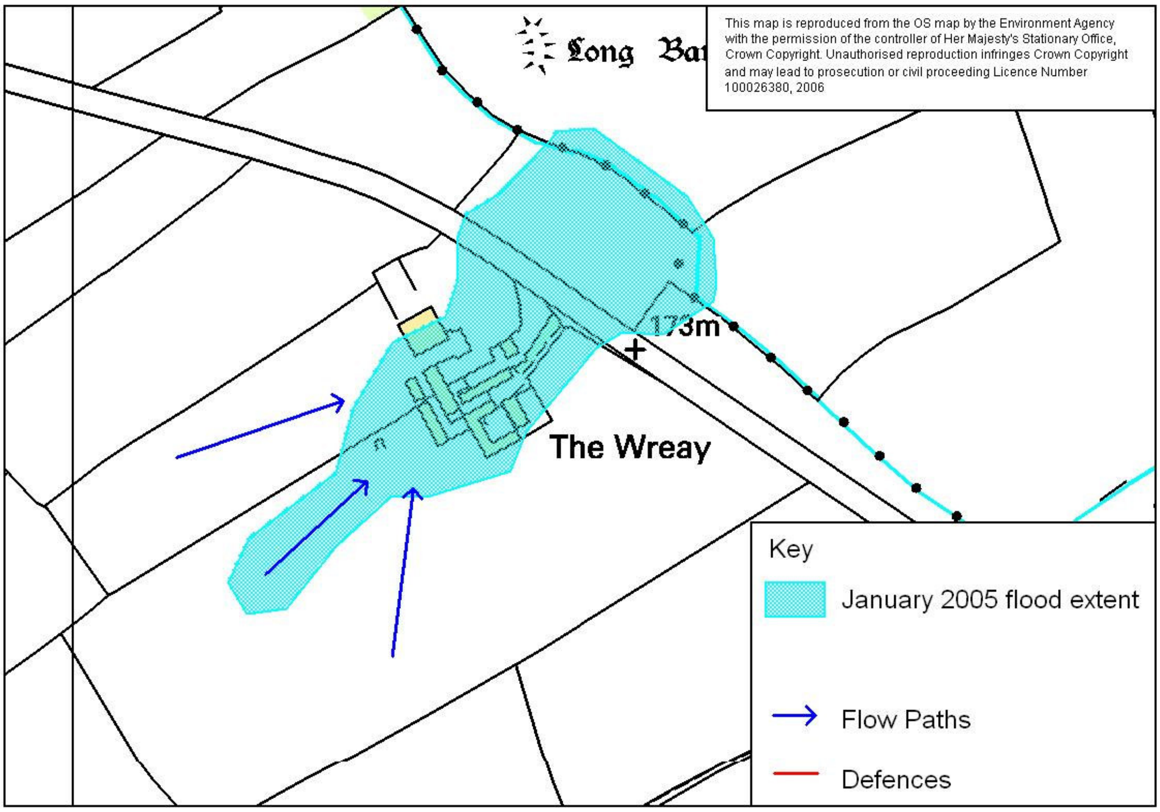
Figure 6-20: Flood outline in Penrith



6.4.10 The Wreay, near Greystoke (Eden)

No. of properties affected: 4 Cause of flooding: Unknown Key Points: • Four out of the six new properties flooded

Figure 6-21: Flood outline in The Wreay



The farm was recently converted into approximately six dwellings, four of which flooded. No watercourse is shown on the maps and it is assumed that the cause was runoff from the fields. There are no wrack marks and the depth of flooding is not known.

6.5 South Lakeland District

6.5.1 Ambleside

No. of properties affected: 8
Cause of flooding: River Rothay, Lake Windermere and overland flow/ highways drainage.
Key Points:

- The Lakeland Properties Distribution Depot, ambulance station and United Utilities' wastewater treatment works were flooded
- At the confluence of Stock Ghyll and the River Rothay, water levels were approximately 2.5m higher than normal

Waterhead

Large amounts of debris from the lake were deposited by the prevailing wind in Borrans Road at Waterhead. Sandbags prevented water entering The Waterside Inn, although the beer garden was inundated and a substantial amount of debris remained when the water receded. The low lying car park at Waterhead was flooded.

Photograph 6-23: Debris left behind by the receding flood waters in Waterhead

River Rothay

On the left bank, most of Rothay Park was inundated. Large slabs of tarmac from the footpath in the vicinity of Miller Bridge were lifted and carried across the grass. The defence level downstream of the Miller Bridge House Gauging Station is high and the river was contained. There was wrack less than 0.5m from the top of the bank. The water in Rothay Park flowed over the wall on the north side of the children's playground. It flowed through the playground, washed out much of the ground and demolished a fence. It flowed over the football pitch, through the sewage treatment works and flooded some of the properties around the business park. These include the Lakeland Distribution depot, Unit One Rothay Holme, the ambulance station and Huddlestones Gas Company.

Photograph 6-24: Slabs of tarmac in Rothay Park had been carried away by the flood waters

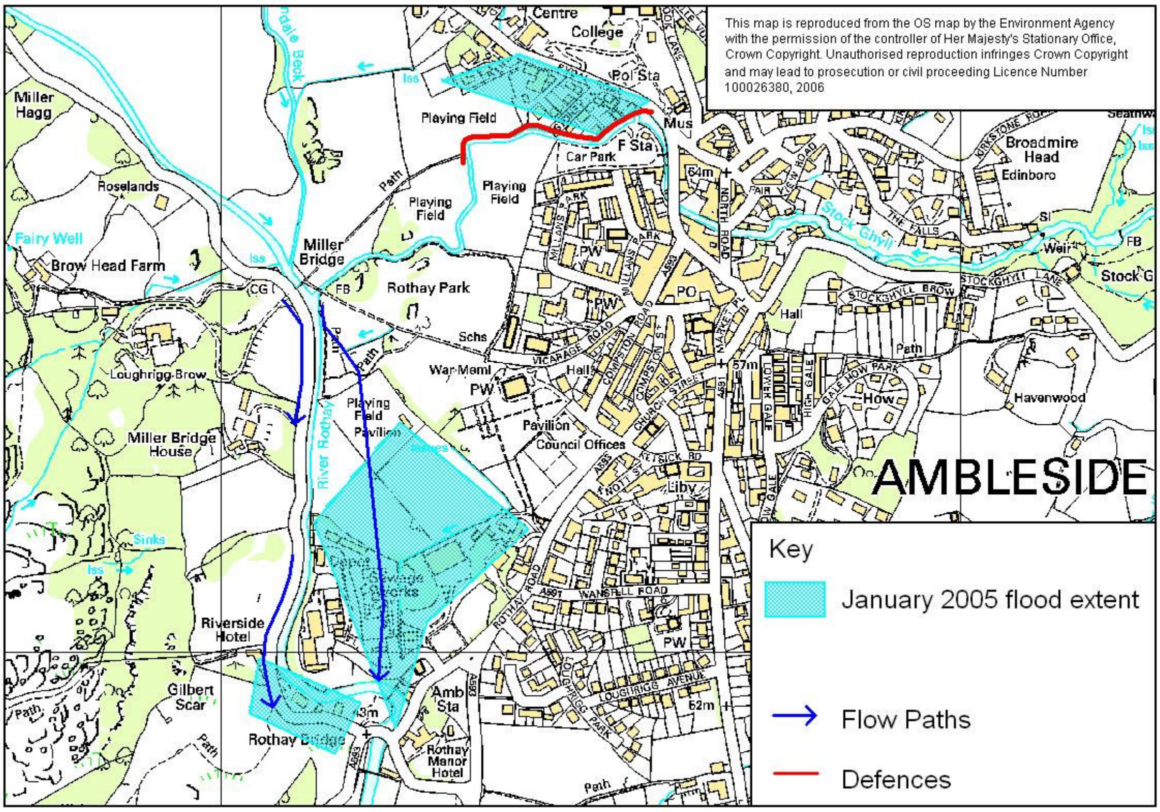
On the right bank, the water was 1 to 2m deep downstream of Miller Bridge, along Under Loughrigg Road. A boundary wall at Miller Bridge House collapsed. Immediately downstream of the Miller Bridge House Gauging Station, the river side wall collapsed. Water flowed past the Riverside Hotel and probably did not affect it directly, although the grounds and car park were flooded. Low lying properties on the right bank just downstream of the hotel were also probably affected but it is not known to what extent.

Stock Ghyll

There is a flood defence along the right bank of Stock Ghyll which protects properties in the Stoney Lane area. There was no reported flooding from Stock Ghyll, although there was evidence of a small amount of out of bank flow. Any further flow would have resulted in flooding of the property around Stoney Lane, and the police and fire and rescue stations.

At the confluence of Stock Ghyll and the River Rothay, water levels were approximately 2.5m higher than normal and there was flooding over the top of the bridge railings.

Figure 6-22: Flood outline in Ambleside

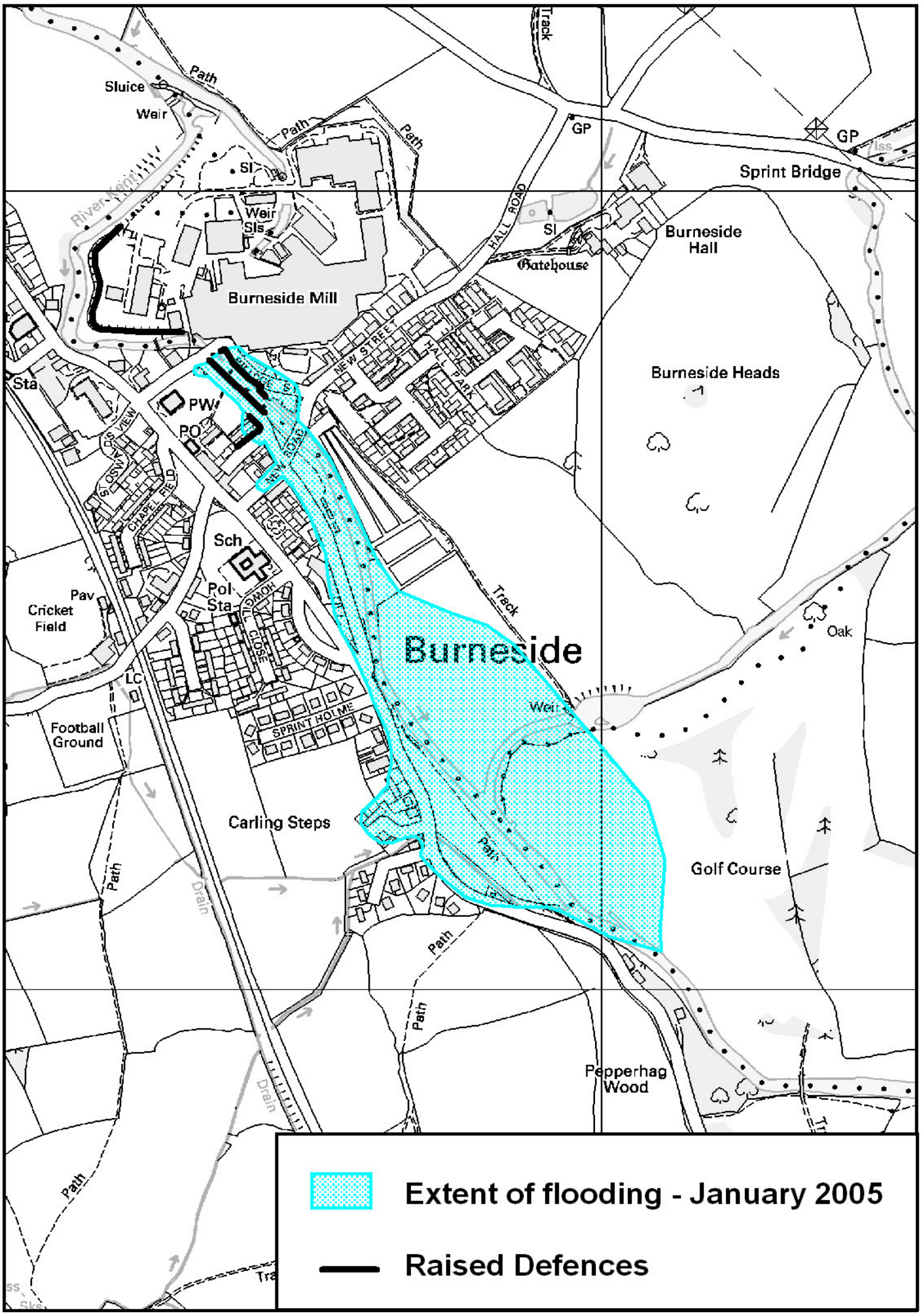


6.5.2 Burneside

No. of properties affected: 3 Cause of flooding: River Kent

Three houses in the area were flooded and a significant amount of damage was caused by fallen trees in the area.

Figure 6-23: Flood outline in Burneside



3

6.5.3 Grasmere

No. of properties affected: 1 Cause of flooding: River Rothay

Rothay Lodge was flooded to an unknown depth. Although water did overtop the wall of the Rothay Garden Hotel, it was not flooded.

6.5.4 Kendal

No. of properties affected: 107
Cause of flooding: River Kent, ground water and surface water
Key Points:

- The majority of the 40 commercial properties which flooded on the Mintsfeet Industrial Estate also flooded in February 2004
- The flood defence scheme through the centre of Kendal coped very well
- The Kent fell as quickly and was in bank again early on 8 January

The River Kent runs through Kendal. Raised defences protect Mintsfeet Industrial Estate and the Lakeland Business Park. A flood defence scheme through the centre of Kendal was constructed in the 1970s.

Flood Warnings were issued at 1759 hrs and 0018hrs on 7 January, and 0117hrs on 8 January.

The first area to be affected was Burneside on 7 January, when the River Kent rose and flooded Carling House at around 2200hrs. The river also overtopped the banks upstream of New Road Bridge and bypassed the bridge. A tree was later found lodged against the bridge, which may have lead to the water coming out of bank. In total, nine properties were flooded upstream of the bridge, some from overtopping and others from groundwater/surface water. The general depth of flooding was approximately 300mm.

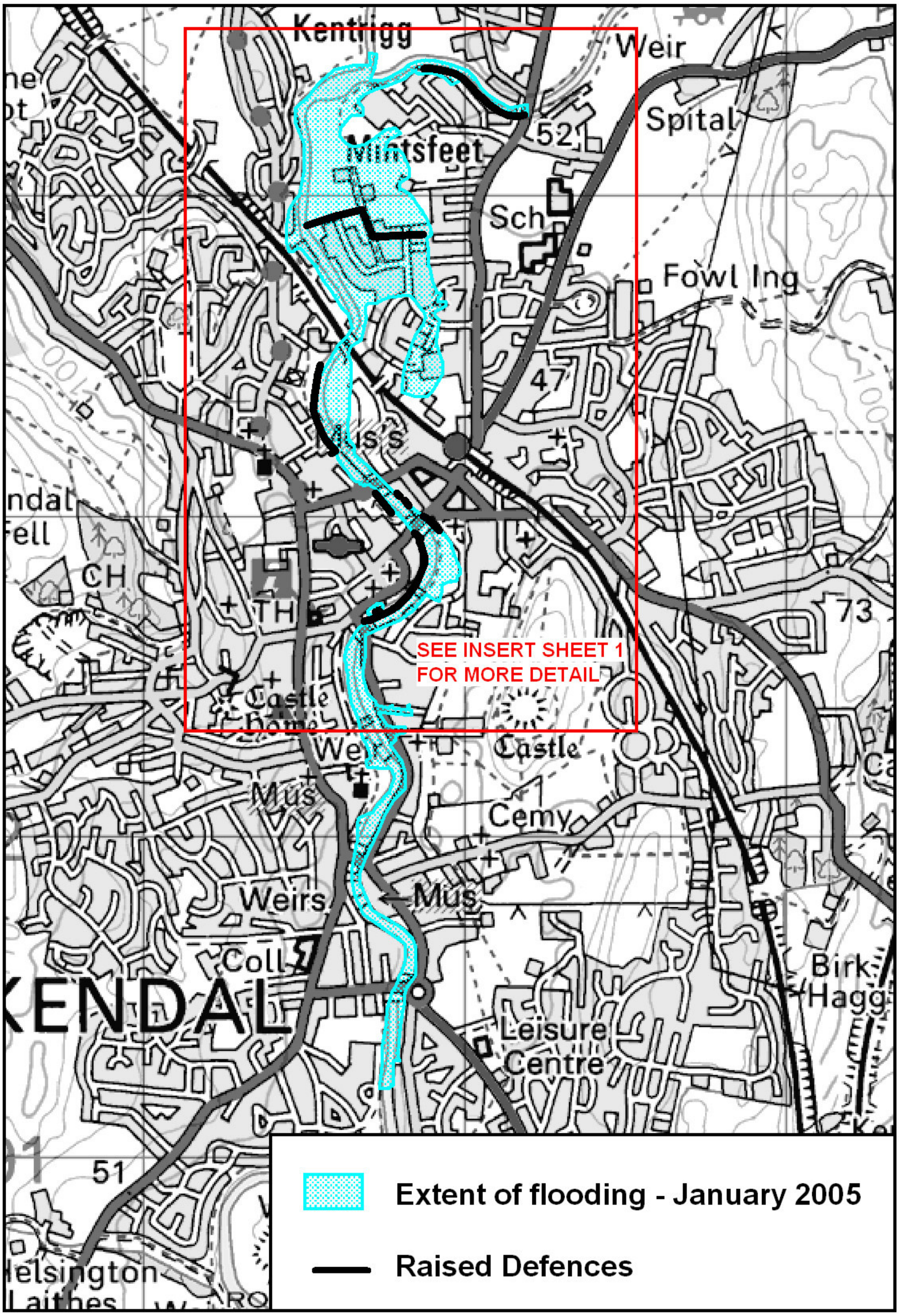
Mintsfeet suffered the worst with approximately 20 residential properties and 40 commercial properties flooded to a depth of 0.5m. Just upstream, there was minor flooding at the Lakeland Business Park; the embankment here was raised following the February 2004 event. The complication of Aikrigg End prevented a similarly quick and easy solution for Mintsfeet.

In the town, properties flooded at Busher Walk, which is an area with a long standing history of flooding. The defences at Aynam Road were overtopped for the first time. No breaches occurred.

The Environment Agency's Risk Management and Operations Delivery operatives were present in Kendal during the event.

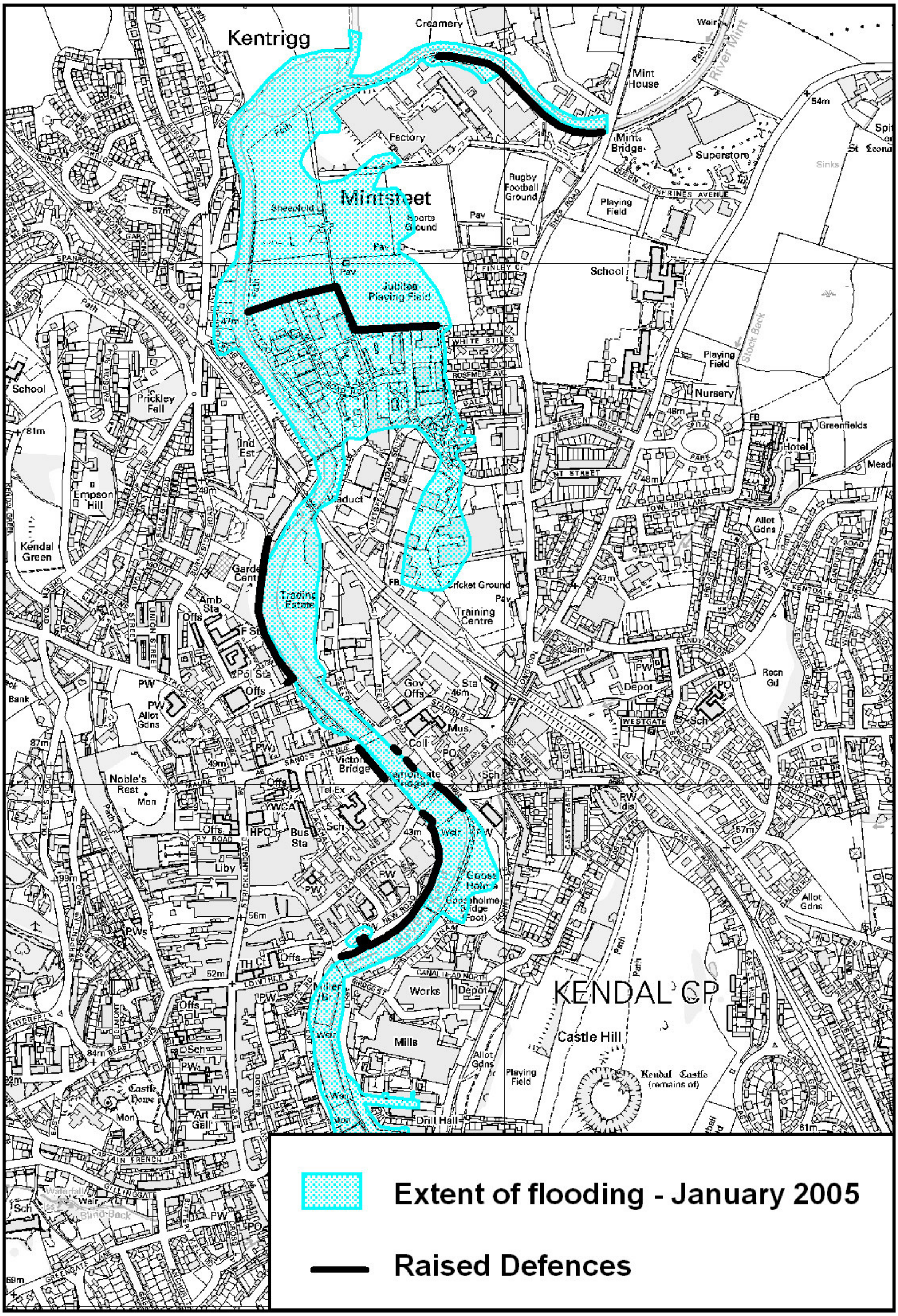
The main areas affected were Burneside, Mintsfeet, Busher Walk and Aynam Rd. In Burneside 16 properties were affected around Carling House and Junction Cottages. In total 60 properties flooded in Mintsfeet and many of the 40 commercial properties also flooded in February 2004. Six properties in Aikrigg End, ten in Busher Walk and 15 in Aynam Road were also flooded.

Figure 6-24: Flood outline 1 in Kendal



P:\120653_CumbriaFloodsReport_PSC\60_Generated_documents\FloodOutlines.wor

Figure 6-25: Flood outline 2 in Kendal

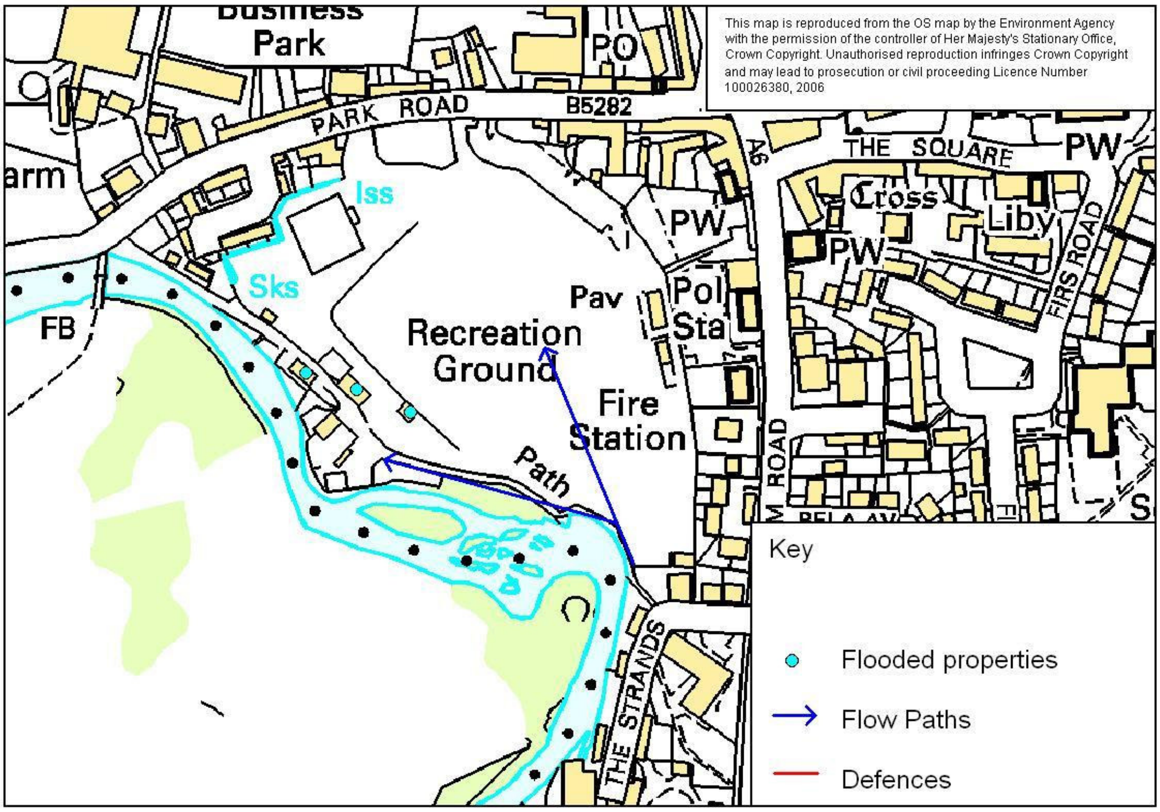


6.5.5 Milnthorpe

No. of properties affected: 3 Cause of flooding: River Bela and surface water Key Points: • The River Bela overtopped the right bank at various locations • The water was approx 0.5m deep along the river side lane

The River Bela overtopped the right bank in various places between The Strands and Park Road. Water flowed onto the football pitch and the clubhouse. The water was approximately 0.5m deep along the river side lane and flooded two riverside cottages. The newer property nearby appears not to have flooded.

Figure 6-26: Flood outline in Milnthorpe



6.5.6 Rydal

No. of properties affected: 1 Cause of flooding: Overland flow/highways drainage

Nab Cottage flooded from overland flow/highways drainage. The tide mark at Rydal Water was 1.5m higher than normal.

6.6 Total Number of Properties

The total number of properties, both business and residential, that flooded in the county during January 2005 is given in Table 6-2.

Table 6-2: Number of flooded properties across Cumbria

Area	Total Number Affected	Watercourse	Return Period (years)	Additional Sources of Flooding
Appleby	53	Eden		
Carlisle	1865	Petteril	75	Surface water, ground water and Little Caldew
		Caldew	75	
		Eden	175-200	
Cockermouth	149	Derwent	75	Rising water table and highways drainage
		Cocker	28	
Kendal	107	Kent	50	Ground water and surface water
Keswick	198	Greta	75	Surface water, sewage, Cuddy Beck and Cuddy Beck tributary
Penrith	21	Thacka Beck	-	
Wigton	22	Speet Gill	-	
		Wiza Beck	-	
Ambleside	8	Rothay	-	Lake Windermere, surface water and highways drainage
Blencow	unknown		-	Surface water
Blennerhasset	6	Ellen	25+	Surface water
Brougham	2	Eamont	50	
Bullgill	3	Ellen	25+	
Burneside	3	Kent	50	
Drybeck	4		-	Surface water, overland flow and Dry Beck
Eamont Bridge	35	Eamont	-	
Grasmere	1	Rothay	-	
Maryport	1	Ellen	-	Overland flow
Maulds Meaburn	3	Unknown	-	
Millhouse	4	Caldew	-	Gillcambon Beck and surface water
Milnthorpe	3	Bela	20	Surface water
Newton Reigny	6	Petteril	-	Highway drainage
Rickerby	14	Eden	175-200	
Roe Beck	17	Roe Beck	-	Overland flow
Rosthwaite	Unknown		-	Ground water
Rydal	1		-	Overland flow and highways drainage
Stockdalewath	12	Roe Beck	-	
Wreay	4	unknown	-	
Total	2544			

6.7 Emergency Services

No hospitals were flooded but the Cumberland Infirmary cancelled all non-emergency operations because of the power cuts. It used generators to treat emergency cases and undertake urgent operations. Some patients were transferred by air ambulance to the West Cumberland Hospital in Whitehaven. Approximately 120 people were treated at the hospital over the weekend for injuries or illnesses related to the flooding. Normal services were restored by 11 January.

Keswick Hospital lost its power supply and when the floods started to threaten the building, staff decided to transfer patients to Penrith Hospital.

The ambulance service struggled to reach people because of the flooding and roads blockages. Assistance with the evacuation of residents was provided by the MoD, two air ambulances which were scrambled from their bases in Teeside and Blyth, neighbouring NHS ambulance services, particularly from Scotland, and voluntary groups.

Photograph 6-25: Ambulance trapped by flood water in Carlisle

The police stations in Carlisle, Penrith and Appleby suffered severe flooding. The former was flooded to a depth of 2.5m and most of its vehicles were damaged. Over 18 months later the police in Carlisle are still in a temporary police station in the city. A permanent new site is being sought rather than returning to Rickergate Station. The closure of the Carlisle Police Station is the only closure of a major police station during peace time.

The headquarters in Penrith lost the communications room as a result of the flooding leading to further difficulties during the flooding.

The station in Appleby was flooded to a depth of 1.5m with the damages up to £100,000. The station was not fully operational for five months.

The Fire & Rescue Service also suffered disruption to its operations and the fire station in Warwick Road flooded to a depth of approximately 2.5m. The fire appliances were not damaged. Carlisle Castle was used as a temporary fire station for 10 days after the event.

To assist with the emergency calls and evacuations, fire and rescue crews from all over the county were called into Carlisle. Merseyside and Cheshire Fire & Rescue Service's boat teams provided vital assistance from 8 to 10 January.

Photograph 6-26: The Police Station in Carlisle flooded

Photograph 6-27: Emergency service personnel used boats to get around and the flooded Carlisle Fire Station

New high volume pumps bought by the government as part of the Civil Resilience Programme were moved to Carlisle and were used to lower water levels in several parts of the city. The pumps are able to deal with 8,000 litres of water per minute.

6.8 Local Authorities

An estimate from Carlisle City Council suggests that £350 million worth of damage was caused during the event in that area.

The high winds which brought over a million trees down had a significant impact on the operation of local councils and, for example, restricted the movement of teams trying to provide sandbags. The Barrow-in-Furness area was unaffected by the storm in 2005 although the council were contacted with requests for sandbags by other councils.

Flooding occurred throughout the weekend in the Eden District Council area with the towns of Appleby and Penrith, and the village of Eamont Bridge being particularly affected. The flooding began 24 hours earlier than in Carlisle.

6.9 Schools

"90% of the county's schools were closed on the Monday due to the effects of flooding, structural damage to the building and power cuts" (The Great Flood, 2005). Some schools were closed for months. Three of Carlisle's secondary schools, namely St Aidan's County High School, Newman School and Trinity School were badly damaged and the repair bills ran into millions.

Photograph 6-28: Newman School

North Cumbria Technology College and Norman Street School were used as emergency reception centres for evacuees.

Crosby-on-Eden school also suffered damage. St Martin's College at Ambleside was closed for two days due to lack of power and access problems.

6.10 Businesses

Although the number of businesses that flooded have been included in the figures in Sections 6.2– 6.5 there are some issues which relate to businesses only which will be discussed here.

Some smaller businesses are known to have relocated or closed due to the damages resulting from the 2005 event. These were mainly in the Caldewgate and Willowholme industrial areas of Carlisle. According to Communities Reunited, 300 businesses were flooded in Carlisle and approximately half of them have relocated or closed down as a result of the flooding.

The Cumbria Business Recovery Group commissioned a survey of businesses into the cost of the storms and floods.

Photograph 6-29: A Keswick business clearing up

The survey obtained results for 666 businesses throughout Cumbria, with 601 located in Carlisle. Although 559 of the businesses were affected in some way only 107 were directly affected by flooding.

The survey was carried out in April/May 2005 by which time 74 of the flooded businesses were trading normally, 63 from the original premises and 11 from alternative premises. 21 businesses were trading to a limited extent most from their original premises and 11 were not trading at all. Most of the respondents expected to be trading fully again by November 2005.

In comparison, of those businesses affected by the storm but not flooded, 99% were trading fully from the original premises.

The estimated total damage costs for those businesses which responded was £14.4 million, plus £4.4 million for lost business.

The general impression gained from the survey was that business owners, although pessimistic about the short term effects on Carlisle, were hopeful that by January 2006 the impacts of the storm and flooding would have been dealt with.

Photograph 6-30: Booths supermarket in Keswick that was closed for 2 days

Following the flooding, Risk and Policy Analysts (RPA) were commissioned by the Environment Agency to assess the impact on non residential assets, services and infrastructure in the Caldew and city centre areas of Carlisle. RPA questioned several major organisations and the findings are summarised in Table 6-3.

Table 6-3: Reported damages from consultation (RPA, April 2005)

Organisation	Direct Damages	Indirect Damages	Details of Damages Incurred
Civic Centre (Carlisle City Council)	£4,000,000	£2,000,000	Indirect damages include costs of having to move to temporary offices and disruption to staff.
Cumbria County Council	£1,100,000	£3,000	Bellwin insurance claim, including emergency response (£140,000), disposal of property damaged by flood (£120,000) and work on highways (£890,000), additional teaching cover (£3,000).
Fire station	£72,000 + £20,000		Loss of ICT, telecomms, 3 vehicles, 1 ATV, furniture/lockers, etc. for Carlisle Fire Station only. Additional £20,000 includes damage to vehicles and equipment whilst on emergency calls.
Network Rail	£2,500,000	Damages not broken down	Damages related to trains that would have travelled into or through Carlisle during their journey and which were either cancelled, stopped partway or delayed.
Police	No value given	No value given	Relocation of staff to Penrith with associated extra travel costs and strain on resources.
Stagecoach bus garage	£3,000,000	£150,000	Write-off of 85 vehicles, including clean-up/repair/loss of stock costs of £470,000 and £220,000 for replacement of plant, equipment, phones, etc. Relocation to Kingmoor Park: £85,000. Two days lost – loss of £30,000 revenue and three days disruption: loss of £30,000 to £40,000. Long-term effects saw reduction of 10% in takings, now reduced to 2% - may be linked to loss of 24 accessible buses (disadvantaged elderly/disabled).
United Utilities	£8,000,000	Damages not broken down	Relate to damages to electricity: £5,000,000; wastewater: £2,000,000 and water: £1,000,000.
Notes: All damage estimates are given to a maximum of 2 significant figures.			

Due to their nature, indirect damages are often more difficult to quantify and as can be seen in Table 6-3 there is not a direct relationship between the value of direct and indirect damages.

A further questionnaire was issued to businesses by Black & Veatch as part of this study. Businesses in all affected areas were contacted including Appleby, Cockermouth, Keswick and Wigton. Due to the available information for Carlisle, only a few companies in the city were contacted

Approximately 100 businesses were contacted. Replies were received from 42 and a further seven replied that they had not been affected by the flooding. Some of the respondents had not suffered any financial cost as a result of the minor flooding or power loss. Others had not quantified their costs. There is only financial information available for 23 of the businesses, see Table 6-4**.** Attempts to contact the non-respondents met with little success.

The majority of respondents were affected by river, surface water and foul water flooding.

Table 6-4: Maximum losses per sector for respondents to questionnaire

	Maximum losses per sector (£k)						
Town	**Retail**	**Office**	**Ware house**	**Non-Bulk**	**Factory**	**Other**	**Depth (m)**
Ambleside			750				1.3
Appleby	263	111		30			-0.01 - 3
Carlisle							4 - 5
Cockermouth	11.5						0.12 - 2
Keswick	200				22		0.1 - 1
Penrith	10					2	0.02 - 0.3
Wigton				10	38		0.1
Total (£k)	**484.5**	**111**	**750**	**40**	**60**	**2**	
No. of businesses	**14**	**3**	**1**	**2**	**2**	**1**	

The direct/indirect split for the sectors differ. The retail sector has a 50:50 split whereas for warehouses almost all of the damages are direct (85%).

6.11 Residential Properties

According to Communities Reunited, a service set up in Carlisle to help people affected by the events of 2005, only 79 homes of those that sought advice were not covered by insurance. This is 4% of the total number of properties flooded in Carlisle; it includes businesses and residential properties.

6.12 Social damages

The more intangible effects of a flooding event include the sentimental value of the possessions lost, the concern people may have that it will happen again and the stress involved in being able to do little to prevent the flood waters entering their property. Although such effects are readily acknowledged to be significant, there is no effective method of assigning an economic value.

Communities Reunited gathered information on the impacts on flood victims' health from those who contacted them for help and advice. The problems reported included:

- Sleeplessness
- Irritability
- Loss of motivation and self worth
- Crying/easily upset
- Feeling low
- No energy
- Unable to focus or make decisions
- Sadness
- Nervousness
- Tiredness
- Loss of confidence
- Anxiety
- Panic attacks
- Sex life affected
- Unable to relax
- Impatience

Approximately 320 homes were still uninhabitable in May 2006 due to ongoing building works. The lack of builders was a major difficulty for those affected by the flooding especially in Carlisle where so many homes needed work carried out. Difficulties were also experienced due to “cowboy” builders taking advantage of the situation. This led to substandard repairs being made to homes which lead to further problems and more expense for already vulnerable people.

Photograph 6-31: Many possessions were contaminated by flood water

6.13 Services

During the event, the equivalent of 18 month’s worth of faults were reported in one day. By midnight on 8 January, 170,000 homes were without power. In total, more than 250,000 homes and businesses in Cumbria and north Lancashire were affected by the power failures. Power to 175,000 customers was restored the same day. United Utilities had in excess of 1000 staff working around the clock to repair the damage to their networks and assets. The cost of restoring the supply in Carlisle alone was £4.5 million.

The electricity sub-station at Willowholme was under 1.5m of water on 8 January, which cut off power to 60,000 properties. This is also the Carlisle Bulk Supply Point, where the electricity supply from the national grid transfers to the UU distribution network. Records show that the site only flooded previously in 1968 when minor flooding occurred. The fire and rescue service pumped out the site using high volume pumps which allowed the restoration of the majority of supplies in Carlisle the following day. When the water level was lowered, UU employees filled over 3,000 sandbags to temporarily protect the sub-station in case the level rose again. Since the event, UU have installed flood defences to protect their key assets at Willowholme. 13 other sub-stations in Carlisle flooded.

There was major flooding of UU's wastewater infrastructure across Cumbria and North Lancashire; 117 sites were affected and the network in Carlisle flooded. By the early hours of 9 January, their water supply operations were affected and 18 water treatment works out of a total of 137 were disrupted. All the affected sites were visited within 24 hours of the water level dropping and, where required, generators were supplied. Other UU facilities that were flooded included the Keswick Pumping Station and the wastewater treatment works in Ambleside.

BT services were out of action. Once the flood water receded, engineers from around the country were brought in to help repair damage. The mobile phone network was down due to the lack of power and this hampered the emergency services' response.

The Royal Mail cancelled deliveries in Carlisle during the floods. Deliveries throughout the county were hampered due to flooding and blocked roads.

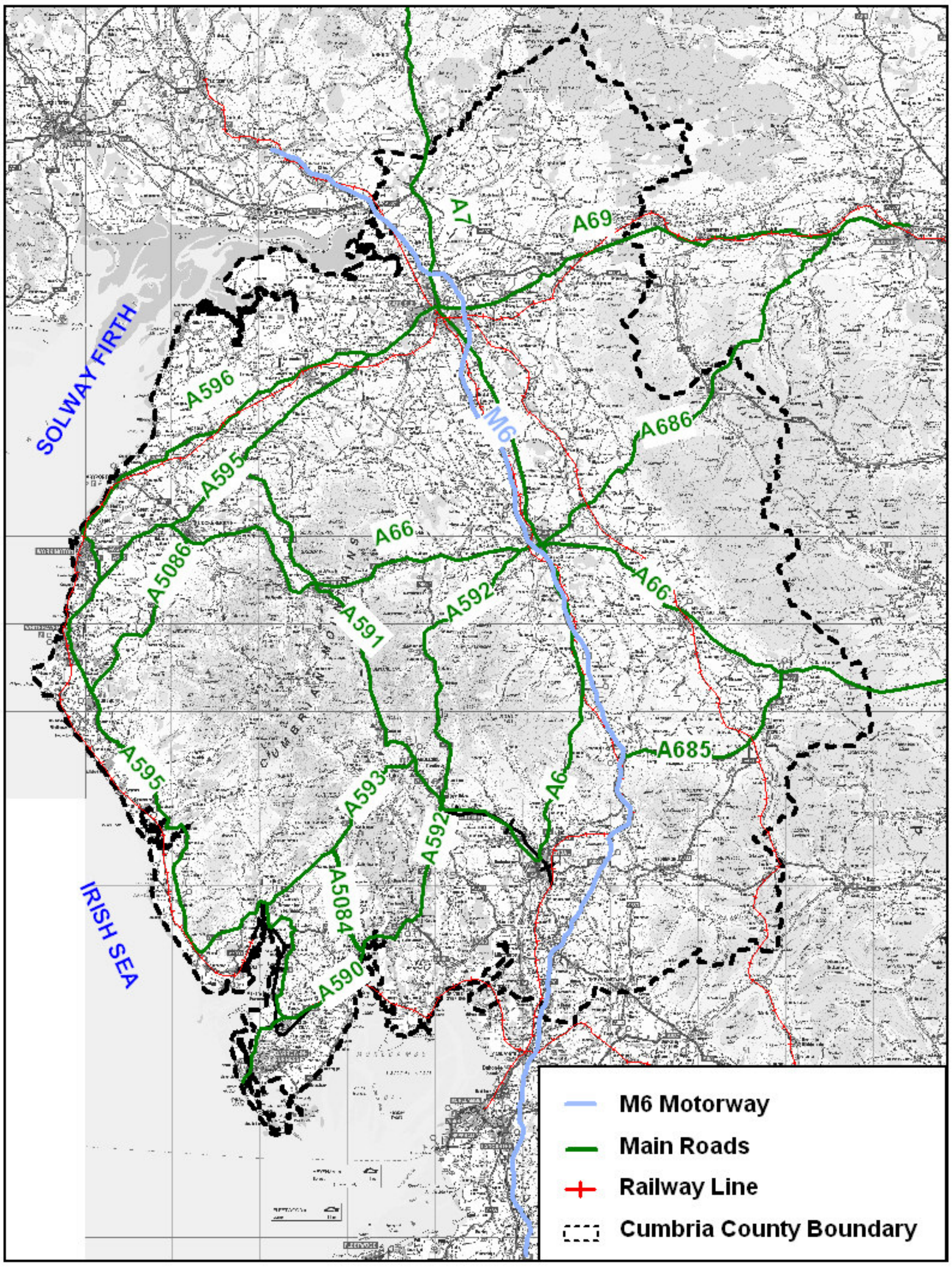
6.14 Roads

Photograph 6-32: Impassable road at Kirkoswald

(Source bbc.co.uk/cumbria)

Although there was considerable disruption to the motorway and trunk road network, the majority of this was due to the high winds. The M6 was closed for some hours due to blown over vehicles and as a precautionary measure due to the very high winds. Many roads were closed due to fallen trees. The Highways Agency report that significant costs were incurred in repairing the damage.

Figure 6-27: Main Roads and Railway Links



The A66 at Temple Sowerby was closed for two hours during the early hours of 8 January when the River Eden overflowed. The road was re-opened by approximately 0600hrs when the river level dropped. The A69 was closed for two days due to flooding at Warwick Bridge.

The A66 was closed at Eden Bridge for several hours by flooding. The A66 and M6 are the only north – south crossing points over the Eden.

There was also minor flooding on the A595 and A590 but both remained open.

Cumbria County Council is responsible for the maintenance of the majority of roads throughout Cumbria. The cost of repairing storm damage to roads and rights of way was £3.2 million. It is not possible to breakdown this figure other than to identify the cost for each District Council area see Table 6-5.

The A686 at Langwathby Bridge was significantly damaged by the flood waters and was closed for several days.

Photograph 6-33: Road flooded by Ullswater

(Source bbc.co.uk/cumbria – taken by Paula Scott)

Photograph 6-34: River Eden flooding A686 at Langwathby Bridge

(Source bbc.co.uk/cumbria – taken by Michelle Hall)

Photograph 6-35: Damage to A686 at Langwathby

(Source bbc.co.uk/cumbria – taken by Helen Smith)

Table 6-5: Costs for highway and emergency repairs

District Council Area	Cost incurred including emergency costs (£m)
Allerdale Borough Council	1.1
Barrow-in-Furness Borough Council	0.1
Carlisle City Council	0.8
Copeland Borough Council	0.1
Eden Borough Council	0.8
South Lakeland Borough Council	0.3
TOTAL	**3.2**

(Figures obtained from Cumbria CC, 2006)

6.15 Public Transport

Train services in the county suffered significant disruption due to the flooding and high winds. The West Coast Main Line (WCML) was closed at Carlisle due to damage to the line from flooding; it was reopened more than a week later. Virgin Trains had to put on a bus service between Carlisle and Lockerbie. Virgin Trains estimate the costs of the closure were in the region of £7.5m.

Two landslides affected railway lines but fortunately the lines were closed for maintenance. The WCML was affected near Shap Wells Hotel and there was a landslip on the Settle – Carlisle line a few miles south of Kirkby Stephen.

Nearly £4 million of damage was done to Stagecoach's vehicles in Carlisle when the depot was flooded to a depth of 2m. 85 vehicles had to be written off at a cost of £3 million.

Photograph 6-36: Flooding in Carlisle showing the main railway line flooded

74 boats were washed away, including three launches belonging to the Keswick Launch Company.

Photograph 6-37: Keswick Launch Company boats that were washed away

Photograph 6-38: Keswick Launch Company diesel tank and boats that were washed away

(Source bbc.co.uk/cumbria – taken by Frances Bell)

7 FLOOD RISK MANAGEMENT IN CUMBRIA SINCE JANUARY 2005

7.1 Introduction

Since the flooding, the Environment Agency and others have been active to reduce the flood risk and lessen the effects of future flooding on people and properties. This section summarises some of the key work.

7.2 Flood Warning and Forecasting

7.2.1 Flood Warning

Improvements have been made to the existing Flood Warning Areas and new areas were added, based on the knowledge gained from the flooding. These improvements are listed in Table 7-1. The aim was to include properties at risk of flooding where an appropriate warning can be given. In some places, there are properties at risk but it is not possible to give an appropriate warning. These are not included.

Table 7-1: Flood Warning Areas in Cumbria post-January 2005 event

Area	Changed since January 2005	Flood Warning Areas
Appleby	×	Existing FWAs
Armathwaite	✓	New FWA split from Eden Valley FWA
Bolton	✓	New FWA
Carlisle	×	Existing Carlisle FWA
	×	Denton Holme FWA
Cockermouth	✓	Existing and Improved FWA
Eamont Bridge	×	Existing FWA
Eden Hall	✓	New FWA split from Eden Valley FWA
Eden Valley	×	Existing FWA
Egremont	×	Existing FWA
Harraby Green	✓	New FWA
Kendal	×	Existing FWA
Keswick	×	Existing FWA
Low Crosby	✓	New FWA
Penrith	×	No FWA
Rickerby	✓	New FWA made part of Existing Carlisle FWA
Warwick Bridge	✓	New FWA split from Eden Valley FWA

7.2.2 Flood Forecasting

Since January 2005, the flood forecasting tools available to the Environment Agency has been reviewed and improved.

Further simple trigger forecasts have been implemented or improved at the following sites:

- Appleby - additional forecast for Bolton based on Appleby levels
- Eamont Bridge Farm
- Harris Footbridge - Cockermouth. Improvement on existing
- Low Briery - Keswick
- Victoria Bridge - Kendal

Together with other correlations used for flood forecasting throughout the North West Region of the Environment Agency, Table 7-2 lists those that were reviewed and improved for Cumbria.

Table 7-2: Improved correlations for flood forecasting

Location of Flood Warning	Location and river predicted	Flow or level	Upstream Stations
Appleby	Eden at Appleby	Level	Great Musgrave Bridge
Carlisle	Eden at Sheepmount	Level	Great Corby
		Flow	
		Level	Great Corby, Greenholme
		Flow	
Cockermouth	Cocker at South St Footbridge	Level	Scale Hill
Denton Holme	Caldew at Denton Holme	Level	Cummersdale
	Caldew at Cummersdale	Level	Sebergham, Stockdalewath
	Caldew at Denton Holme	Level	
Keswick	Greta at Low Briery	Level	Threlkeld
		Level	Threlkeld, Thirlmere
Eamont Bridge	Eamont at Eamont Bridge Farm	Level	Pooley Bridge, Dacre Bridge
Warwick Bridge	Eden at Great Corby	Level	Udford, Temple Sowerby
Low Crosby	Eden at Linstock	Level	Great Corby, Greenholme
Kendal	Kent at Victoria Bridge	Level	Sprint Mill
		Level	Sprint Mill, Bowston, Mint Bridge

In this review, it was evident that a quadratic regression equation often fitted better than the previously used linear regression.

All three transfer function models, namely Low Briery, Cummersdale and Victoria Bridge, are unchanged. Re-calibration of the former was attempted but a model calibrated to the 2005 flood over predicts all other events. Therefore, the original model was retained but the January 2005 one is available for extreme floods.

The ISIS Eden real-time model was reviewed and improved, and further improvements are ongoing. *Spencer et al* 2006 describe these improvements in detail; refer to Appendix 6. The key improvements are:

- representation of the ungauged inflow catchments
- representation of the floodplain upstream of Carlisle and close to the M6
- the stage discharge equations for the gauging stations

The latter resulted in the most significant improvement and further work is underway.

7.3 Flood Alleviation Works and Schemes

Over the last fifty years or so, major investment in flood alleviation works has occurred throughout Cumbria. These include major schemes in Carlisle, Kendal, Keswick and Cockermouth as well as schemes in a whole number of other locations. This investment has been supported by an annual programme of maintenance on both the defences and the rivers.

Improvements to the defences in Carlisle were being investigated at the time of the event.

Since 2005, a number of improvement works have been completed and these are listed in Table 7-3.

Table 7-3: Completed flood risk management improvements in areas affected by January 2005 floods

Location	Recently Completed Work
Carlisle	Piling 140m of flood bank along Warwick Road to rectify localised low spot. Minor raising and extending of the River Petteril flood banks at their upstream limit in Melbourne Park. Piling 80m of damaged flood bank on the River Caldew, Willowholme upstream of West Coast Railway Bridge. Stabilisation of flood embankment near Willowholme
Penrith	Reconstructed and improved the culvert and debris screen at Watson Terrace.
Keswick	Removed gravel from the river and constructed a new culvert inlet and debris screen at Cuddy Beck.
Appleby	Replaced flood defence gates and reconstructed the Church St flood defence.
Kendal	Improved the Mintsfeet flood embankments.

Table 7-4 lists those flood alleviation schemes which are either ongoing or under investigation.

Table 7-4: Ongoing or potential flood risk management improvements in areas affected by January 2005 floods

Location	Additional Information	Under Investigation	Under Construction
Carlisle	<u>Eden & Petteril Flood Alleviation Scheme</u> – to protect areas of Carlisle (Warwick Road, etc) from flooding.		✓
	<u>Caldew and City Centre Flood Alleviation Scheme</u> – to protect areas from flooding from Rivers Caldew and Eden.	✓	Due 2008-10
Penrith	Scheme to protect against flooding from Thacka Beck	✓	
Keswick		✓	
Cockermouth		✓	
Appleby		✓	
Carlisle – surrounding areas	Etterby Terrace	✓	
	Durran Hill Beck	✓	
	Harraby Green	✓	
	Rickerby	✓	
	Low Crosby	✓	

Implementation of flood alleviation schemes or similar will almost certainly lead to the need to revise flood warning (and possibly forecasting) arrangements at those locations.

7.4 Studies

Two papers written by staff from the Environment Agency are available on the website at www.environment-agency.gov.uk. These are:

- Flood Forecasting using Real Time Hydraulic Models: Lessons from the Carlisle Flood in January 2005, Environment Agency (*Peter Spencer et al*)
- A Multi-Agency Approach to Delivering a Sustainable Flood Alleviation Scheme for Carlisle, Environment Agency (*Jonathan Griffin et al*)

The Catchment Flood Management Plans and flood maps for Cumbria are also available on the Environment Agency's website.

Immediately after the flood, the Environment Agency undertook an extensive survey of levels attained by the flood at various locations. These levels were based on wrack marks or observations during the flood by Environment Agency staff or others. Results of these surveys provided information to plot the flood maps shown in Section 6 and are held at the Environment Agency's Penrith office.

8 CONCLUSIONS

8.1 Meteorology

The heavy rainfall was caused by a strong airflow of unusually warm, moist tropical air, which was forced northwards ahead of an Atlantic cold front. At the end of the storm, the rainfall was enhanced by strong frontal uplift and convection, as a depression centre passed near to the north of the area. There was orographic enhancement over the high ground of Cumbria, namely the rainfall was increased by the presence of high ground.

The rarity of the storm is associated with its length, rather than the intensity of the rainfall. An overall return period of some 100 years (1%) is suggested.

Rainfall totals of more than 200mm were recorded at some gauges. Although significant amounts of rain fell throughout Cumbria, the heaviest was over the high ground of the Lake District, the Howgills and the Yorkshire Dales. The rainfall occurred predominately between midnight on 6/7 January and midday on 8 January. At some locations, the return period of the rainfall was 175 years (0.57%) and many gauges had totals with return periods in excess of 50 years (0.5%).

The rainfall was accompanied by hurricane force winds, which themselves caused significant damage and hampered the efforts of the emergency services and others. A meteorological feature referred to as a 'sting jet' is likely to have increased the strength of the winds, although it would have had little or no effect on the amount of rainfall.

8.2 Hydrology

During the flood, the flows in rivers such as the Eden, Kent and Derwent were the highest on record. The flood peaked in the upper parts of the Eden and Derwent catchments in the early hours of 8 January. The River Kent in Kendal peaked at a similar time. In Carlisle, the River Eden peaked at an estimated 1520 m^3/s at the Sheepmount Gauging Station at 1430hrs on 8 January. This flow has a return period in the order of 175 to 200 years (0.57% - 0.5%). At other locations, the return period was in excess of 50 years (2%).

A notable feature of the event was that flooding was often initially caused by surface water flows as the local drainage networks were overwhelmed. This occurred in locations such as Keswick and Carlisle, and typically happened late on 7 January or early 8 January. There were also instances of flooding caused by groundwater flooding.

Many lakes and reservoirs reached their highest recorded level. Haweswater Reservoir did not start to spill until after the flow peaked downstream in the River Lowther. Thus, it was a factor in reducing the magnitude of the peak. Thirlmere Reservoir had been spilling since Christmas. Nevertheless, such a large reservoir would attenuate flows through it thereby reducing the peak downstream flow.

Studies have been carried out to investigate the effect of the high tide in the Solway Firth during the event. These show that the tide had no effect on peak river levels through Carlisle.

8.3 Hydrometric Network

The vast majority of rain gauges and river gauging stations operated successfully during the event. The telemetry links remained in place, which allowed the recorded data to be transferred back to the Environment Agency's offices.

Rainfall radar is useful to show the movement of the storm. However, it does not provide accurate rainfall data for much of Cumbria due to the distance from the radar station on Hameldon Hill and the effect of high ground.

Since the event, research has shown that the strong winds may have caused the tipping bucket rain gauges to under record. This was identified in comparisons between these and the standard daily storage gauges, although other factors may be at play. The frequency of the rainfall was estimated using the Flood Estimation Handbook's depth duration frequency model and the preceding point must be borne in mind when considering the results. Ongoing research into the rainfall may result in improvements to the method.

Whilst almost all the gauging stations successfully recorded river levels during the flood, the derivation of flows is problematical. Flows were out of bank at most stations and the rating curves did not extend to such high levels. Since the flood, the stage discharge relationships for a number of stations have been re-examined. This has led to significant changes in the estimates of peak flow. Other such studies are planned

8.4 Flood Warning & Forecasting

The Environment Agency's 'A review of the floods in northern England and North Wales January 2005' has a number of conclusions and recommendations for flood warning and flood forecasting. Hence, this study did not examine flood warning in detail.

The flood warning statistics clearly show that some 50% of the properties in the flood warning areas are not registered to receive a warning from the Environment Agency's AVM system. Since 2005, this has been replaced nationally by Floodline Warnings Direct and there has been a big increase in the number of people registered to receive a telephone warning (now up to 75% across Cumbria). Surface water flooding was significant at a number of locations at this occurred prior to any warnings being issued.

The Environment Agency use four types of flood forecasting model, which vary in complexity. The 'simple trigger' models performed well during the event. Whilst the models performed well, they cannot provide forecasts with a long lead time or predict flood peaks. The correlation models, which relate the upstream level to a downstream prediction, under-predicted flood levels on the Eden and in Keswick. Their poor performance is because the flood levels were significantly higher than those used to calibrate the models. Subsequently, changes were made to five such models.

Only the more complex transfer function model for Kendal performed well. The other such models for Keswick and Cummersdale did not. For the former, the extreme nature of the flood means that a model calibrated on it would not perform well for the more frequent events. At Cummersdale, the poor performance is mainly due to quality of the rainfall radar.

The ISIS real-time model for the Eden at Carlisle is one of the first of its type to be implemented by the Environment Agency. It performed well during the early part of the flood but it did not accurately predict the peak. This was largely because the input flows were under-predicted by the then current stage discharge relationships at the key upstream gauging stations.

The 2005 event illustrates that the nature of such extreme floods can be different to more frequent ones.

8.5 Flood Impacts

More than 2,500 properties were flooded throughout Cumbria, of which some 75% were in Carlisle. It is one of the few recent floods in the United Kingdom that had fatalities associated with it.

The flood had significant social impacts. Many people were affected and a considerable number were in temporary accommodation for months. By May 2006, at least 300 homes were still uninhabitable. The flood victims reported many problems with their physical and mental health. Many experienced difficulties with the repairs to their homes which exacerbated matters. Whilst it is possible to quantify in economic terms, the physical impacts of a flood, it is extremely difficult, if not impossible, to quantify the social impacts

Key infrastructure such as police stations, council offices and schools were affected. The closure of the police station in Carlisle was the first closure of a major station in peacetime.

The flooding and the associated gales affected the electricity, telephone, wastewater infrastructure and the transport network. About a quarter of million houses were affected by power cuts, the M6 and the West Coast Main Line railway were closed. In parts of Carlisle, the telephone network failed and in parts of Cumbria, the mobile telephone network failed due to the disruption in power supply.

The above made the work of emergency services and other agencies more difficult. For example, road closures meant that some key staff were not available. The flooding of the civic centre in Carlisle meant that the Strategic (Gold) command centre had to be relocated to the Cumbria Police Headquarters in Penrith. Although this was affected by flooding, it remained operational.

In terms of damage, it was one of the most significant fluvial floods in the last 50 years. The total damages are likely to be in the order of £500 million. In comparison with other notable recent floods in England, this is less than the Autumn 2000 floods. It is more than the 1998 Northampton floods, which affected about 1100 properties. However, the Cumbria flooding is quite different in nature as it was confined to a small geographic area.

8.6 Flood Risk Management in Cumbria since January 2005

Prior to the flood, the Environment Agency was planning improvements across Cumbria, most notably new flood defences in Carlisle. The huge impact of the flood has served to bring this work forward. The event has also provided a wealth of new information that has helped improve models, and flood forecasting and warning arrangements.

Flood risk management works have been carried in Appleby, Carlisle, Kendal, Keswick and Penrith. In Carlisle, a flood alleviation scheme to reduce the risk of flooding to the Warwick Road area is under construction. Further work is planned across Cumbria.

This page left blank intentionally

9 ACKNOWLEDGEMENTS

The study was undertaken by a team consisting of: -

Black & Veatch
Tim Palmer
Jenny Palmer

Met Office
Brian Golding
Will Hand
Peter Dempsey

Environment Agency
Liz Anspoks
Craig Cowperthwate
Peter Spencer
Maria Nelles
Jonathan Griffin
Les Cornwell

The team would like to acknowledge the help and input from the following: -

- Jim Blease, Suzanne Caldwell, Jeff Davidson, John Dawson, Dave Falcon, Mark Franklin, Andy Frazer, Emma Goodall, Ed Griffiths, Kevin Howarth, Jeff Lawrenson, Iwan Lawton, Brian Leigh, Ben Lukey, Roy Martin, Susan Mossop, Anne Netherway, Gemma Reynolds, Sarah Rogerson, Michael Shankster, Helen Stanley, Susan Taylor, Victoria Townend, Glyn Vaughan, Sharon Weaver, Clare Wheeler and Martin Wilson of the Environment Agency.
- All those who completed the questionnaires
- Paul Hendy, Communities Reunited
- Mike Stevens, Amey Mouchel
- Aileen Sykes, North West Development Agency
- John Ash, Risk Policy Analysts Limited
- Chris Dove, Cumbria County Council
- Peter Walsh, North West Regional Flood Defence Committee
- John Chatterton, Chatterton Associates

This page left blank intentionally

10 REFERENCES

Smith, K. and Tobin, G A. 1979 *Topics in Applied Geography Human Adjustment to the Flood Hazard.* Longman, London .

Environment Agency. 2005 *Managing Flood Risk Dealing with flooding, A review of the floods in northern England and North Wales, January 2005*

Robertson, D and Koronka, P. *The Great Flood Cumbria 2005* Hayloft Publishing Ltd, Kirkby Stephen, Cumbria, CA17 4DJ 2005

Institute of Hydrology. 1999. *Flood Estimation Handbook*, Institute of Hydrology, Wallingford, UK.

Cumbria Business Recovery Group 2005 *Business Survey Summary, December 2005*.

Meteorological Office 1997 *Met Office Forecasters Reference Book*

Hodgkinson, R.A., Pepper, A.T., and Wilson, D.M. 2004. *Evaluation of Tipping Bucket Rain Gauge Performance and Data Quality*. Environment Agency. Science Report W6-048/SR

Risk & Policy Analysts Limited 2005 *Carlisle Floods: Economic Assessment for Commercial Properties in Caldew/City Centre Draft Final Report April 2005*

Cumbria County Council 2006 *Figures for highways damage during the January 2005 event*

This page left blank intentionally