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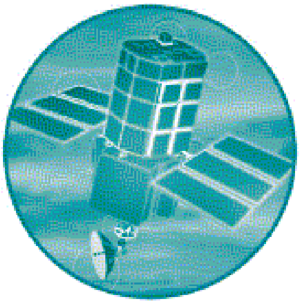

Flood Forecasting - Rainfall Measurement and Forecasting

R&D Technical Report W5C-013/4/TR

DEFRA
Department for
Environment,
Food & Rural Affairs

Environment Agency

Flood Forecasting
Rainfall Measurement and Forecasting

R&D Technical Report W5C-013/4/TR

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EXECUTIVE SUMMARY

The project 'Flood Forecasting – Rainfall Measurement and Forecasting (W5C-013/4/TR) and Real-Time Modelling (WSC13/5)' has two main components:

- Rainfall measurement and forecasting techniques
- Real-time modelling of river levels and flows up to the tidal interface

This project has a number of objectives, the main one being to support an improvement in the quality of operational real-time flood forecasting within the Agency. This project aims to provide a first step in the process of developing practical guidance for flood forecasting and flood warning staff in the use and operation of real-time flood forecasting models.

This report presents the technical review undertaken for the Rainfall Measurement and Forecasting component of the project, and presents information from research papers and reports, attendance at scientific meetings, project experience, and consultation interviews with Agency staff. The report presents:

- an overview of operational rainfall measurement and forecasting in England and Wales. Information is presented on current limits of predictability; precipitation measurement by radar and rain gauges; operational forecast techniques (for a range of forecast lead-times from 0 to 10 days ahead); and 'nowcasts' (forecasts up to 6 hours ahead).

- an assessment of how rainfall measurements and forecasts are currently used within the Agency for flood warning and forecasting, and problems which have been encountered.

- an assessment of existing shortfalls in meeting operational flood forecasting and warning needs, considering the range of operational techniques available now, and under development, from nowcasting procedures though to regional scale numerical modelling systems. The assessment of unmet needs provides the basis for proposed future R&D work.

- a detailed review of the practice and limitations of rainfall measurement using weather radar (including basic weather radar theory, sources of errors and recent developments); a review of rainfall forecasting techniques (including numerical weather prediction models, forecasting methods for convective rainfall, ensemble predictions, the Nimrod and Gandolf systems, and other recent developments) and a listing of regional rainfall measurement and forecasting issues and examples identified by Agency flood warning staff and summarised in previous R&D reports.

GLOSSARY

TERM	DEFINITION/DESCRIPTION
Anaprop	Anomalous propagation – the downwards bending of a radar beam on encountering strong vertical temperature or humidity gradients
Attenuation	In these guidelines, absorption of the power of a radar signal by precipitation
Automatic Weather Station (AWS)	An instrument for measuring climate data in real time (typically 15 minute intervals). Data may be stored on a logger, or transmitted by telemetry
Bright Band	The layer of melting snow which occurs in frontal rainfall resulting in increased reflection of a radar beam
Clutter	The reflection of a radar beam from non meteorological targets (e.g. ground clutter)
Cyclops	A new radar signal processing system being rolled out by the Met Office during 2001 and 2002 to all UK radar sites
Daily Rainfall Forecast	A Met Office product for the Agency, giving forecast rainfall totals over predefined periods up to 2-4 days ahead
ECMWF	The European Centre for Medium Term Weather Forecasts (located in Reading, UK)
Ensemble	Two or more alternative realisations of future rainfall or flow conditions based on alternate initial conditions, parameter values etc
EnviroMet®	A prototype Met Office/NW Region GIS/Internet based system for displaying meteorological information, e.g.radar, rainfall accumulations, on a catchment basis
Flood Estimation Handbook (FEH)	The standard UK reference for design flood estimation
Flood Warning Area	A defined area within which the Agency undertakes to provide a 4 stage flood warning service
Forecasting Point	One or more points with a Flood Warning Area for which levels and/or flows are forecast as a basis for providing warnings
FTP	File Transfer Protocol; a standard for electronic exchange of data
GANDOLF	A thunderstorm forecasting system developed from combined Met Office/Agency research in Thames Region
Heavy Rainfall Warning	A Met Office product to provide the Agency with forecasts of rainfall above given thresholds over Agency defined areas, typically 12-24 hours ahead
HYRAD	A weather radar display and forecasting system developed by the Centre for Ecology and Hydrology (Wallingford) and used in several Regions
Mesoscale model	A Numerical Weather Prediction model of high spatial resolution/limited spatial extent
Meteosat	The WMO's network of geostationary meteorological satellites
MORECS	A Met Office product providing estimates of soil moisture weekly on a 40 km grid
MOSES	The successor to MORECS providing soil moisture estimates at higher resolution (hourly at 5 km) and additional information (runoff, snow cover etc)
Nexrad	The US National Weather Service (NWS) national network of high resolution S-band doppler radars
Nimrod	The Met Office's 'nowcasting' system providing both radar actuals and forecasts at 1-5km/5-30 minute resolution from 0-6 hours ahead
NIWRDS	National Interim Weather Radar Display System – a new software system

	for displaying radar and Nimrod data and forecasts being rolled out to the Agency during 2002
Nowcast	Conventionally taken to be forecasts for 0-6 hours ahead
Numerical Weather Prediction (NWP)	Computer models in which the atmosphere, oceans and land surface are modelled on a three dimensional grid
Orographic growth	Growth in rainfall intensity at low level over hills
Quantitative Precipitation Forecast (QPF)	Any forecast which provides estimates for rainfall depth and spatial extent and/or location
+Polar Data	The raw form in which radar rainfall reflectivity data is measured before conversion to Cartesian (grid based) coordinates
Potential Evaporation (PE)	The evaporation from an open body of water (or saturated land surface) conventionally estimated from the Penman equation
Real Time Modelling	Here taken to mean quantitative forecasting of river levels and flows using measured or forecast rainfall or flows higher in the catchment
Snow Pillow	An instrument for estimating snow depth which relies on detecting the weight of snow which has fallen
Trigger	A river level above which flood warnings are issued
WRIP	Weather Radar Information Processing system – a combined radar processing and flood forecasting system used in South West and North West Regions

1. INTRODUCTION

1.1 Background

The Agency aims to deliver Accurate, Reliable and Timely forecasts of flooding at locations in England and Wales where the benefits justify the costs and where the provision of this service is technically possible. Achieving this aim will contribute to reducing the risks associated with flooding by:

- Supporting the effective delivery of flood warnings to save life, reduce damage to properties and minimise disruptions to communication lines;
- Providing information upon which sound decisions can be made on the operation of river systems and river control structures during flood emergencies.

The Agency states in its Customer Charter (Environment Agency, 2001a) that, regarding warnings;

> *"We will aim to do so at least two hours before flooding happens in areas where a service can be provided.."*

As part of its Flood Warning Service Strategy for England and Wales (Environment Agency, 1999) the Agency states that it aims to achieve this target by leading work on the best techniques for forecasting and promoting the innovative use of technology that will improve the ability to predict floods.

In a post-incident report on the Autumn 2000 floods (Environment Agency, 2001b) the Agency concluded that, in Regions where Real Time flood forecasting Models were available, these were mainly used only indicatively to support decisions to issue flood warnings. This reflected a lack of confidence in the model output, in turn attributed to a lack of confidence in weather forecast information and irregular model recalibration and updating (often reflecting a lack of adequate resources). The report also highlighted that, although model runs did in some cases produce accurate estimates of peak flows, the timing and duration of predicted flooding could be inaccurate.

The establishment of the Agency's National Flood Warning Centre (NFWC) now provides a focus for ensuring a consistent approach to the further development of operational flood forecasting in England and Wales. Following a concerted action workshop in February 1999 (Environment Agency, 2000a), the present project was identified for inclusion in the portfolio of R&D projects, and has the aim of identifying how the Agency may make best use of **rainfall measurements and forecasts** and **real time models** for flood forecasting and warning. This will be achieved through an analysis of the current situation and comparisons with customer-driven needs for accurate and timely flood warnings, and the production of Guideline documents.

The project "Flood Forecasting – Rainfall Measurement Forecasting (W5C-013/4/TR) & Real Time Modelling (WSC013/5)" has two main components:

- Rainfall measurement and forecasting techniques
- Real time modelling of river levels and flows up to the tidal interface

The project was undertaken by a consortium of WS Atkins Consultants Ltd, University of Salford, JB Chatterton & Associates and Edenvale Modelling Services. The project was overseen by a Project Board which included representatives from the National Flood Warning Centre and regional Agency staff.

1.2 Layout and Contents of Report

The report consists of a Main Report and Appendices as follows:

Chapter 2 reviews existing observation and measurement techniques for flood warning. Primarily this chapter focuses on rainfall, and reviews the use of tipping bucket raingauges, weather radar and satellite imagery. The chapter also covers automatic weather stations, and snowmelt and snowcover observations.

Chapter 3 reviews existing rainfall forecasting techniques – from Numerical Weather Prediction models, to ensemble forecasting and radar only techniques.

Chapter 4 reviews the existing Met Office Nimrod, Heavy Rainfall Warning / Daily Rainfall Forecasts and MOSES products.

Chapter 5 presents relevant international experience and developments, identified from a review of recent literature. The chapter includes reviews of the American Nexrad radar network, Autocaster, and Warning Detection Support System, the Canadian Radar Display System, recent developments in Germany undertaken by the German Weather Service, as well as the preliminary findings of a recent international inter-comparison of rainfall forecasting systems.

Chapter 6 describes the various methods used to assess rainfall measurement and forecast accuracy, including a review of the performance statistics used by the Met Office, before presenting a review of the accuracy of rainfall measurements and forecasts (for both short and long term forecasts)

Chapter 7 considers how the techniques discussed in Chapters 2 and 3 are presently used within the Agency for flood warning and forecasting, and problems which have been encountered. Points discussed include the requirements (in terms of accuracy etc) for real-time weather radar data, and for archiving flood event data and the associated radar frames.

Chapter 8 presents a structured listing of over 30 candidate R&D topics to address meeting operational flood forecasting and warning needs.

References A literature review has been undertaken as part of the project. Reports and papers referred to within the main report are listed in this section.

Bibliography A substantial body of Agency Research and Development work already exists and has been described in previous R&D and other reports. The most relevant reports are listed in this section.

Appendix A An amended version of the generic Flood Forecasting Glossary and listing of acronyms/abbreviations produced and maintained by the National Flood Warning Centre. The glossary supplements the report-specific glossary provided at the start of this report.

Appendix B A detailed review of the practice and limitations of rainfall measurement and forecasting using weather radar. Topics considered include the basic theory, sources of errors and recent developments.

Appendix C A detailed review of the main rainfall forecasting techniques which are currently available, including numerical weather prediction models, forecasting methods for convective rainfall, ensemble predictions, the Nimrod and Gandolf systems, and other recent developments.

Appendix D A listing of regional rainfall measurement and forecasting issues and examples identified by Agency flood warning staff and summarised in previous R&D reports. The information has been reproduced verbatim and forms the foundation of the issues described in this report.

Appendix E A list of the papers presented at the recent American Meteorological Society 30th International Conference on Radar Meteorology in Munich (July 2001) and at the NERC Town Meeting on Quantitative Precipitation Forecasting (London, 2001)

Appendix F Short Form A's for potential R&D projects.

Appendix G Information on the Second Generation Meteosat satellite. This has been reproduced verbatim from the European Space Agency website (reference provided in the Appendix).

- **Guidelines for Rainfall Measurement and Forecasting** aimed mainly at operational flood forecasting staff, and considering how the Agency may make best use of existing rainfall measurements and forecasts for flood forecasting.

- **A Technical Report** presenting a detailed review of the current state of the art in rainfall measurement and forecasting, existing Agency use of rainfall measurements and forecasts for flood forecasting, and identification of shortfalls and future R&D needs to address the shortfalls.

The Guidelines are a succinct document for Agency staff and consultants, indicating the key decisions that Agency staff needs to make, and the information required, in order to fully utilise rainfall measurements and forecasts for flood forecasting. The Guidelines provide the essential technical support information in an abbreviated format, and full supporting technical information is provided in this Technical Report. The Technical Report is therefore an essential companion reference volume that should be used alongside the Guidelines. To assist in this, the Guidelines refer out to the appropriate sections in the Technical Report.

This technical report presents the findings of the work undertaken in the rainfall measurement and forecasting component of the project. The report has been prepared using information derived from research papers and reports, attendance at scientific meetings, project experience within the consultants, and interviews with Met Office and Agency staff.

2. DETECTION AND OBSERVATION

2.1 Tipping Bucket Rain Gauges

2.1.1 Introduction

For flood forecasting applications, real time rain gauge measurements of rainfall are useful on a sub-daily basis for input to rainfall runoff and other flow forecasting models. Daily rainfall totals can also be useful to update the state of the internal variables (e.g. antecedent conditions) but, due to the real time requirement, are usually derived from sub-daily data rather than storage gauges. Therefore, this section focuses solely on tipping bucket raingauges.

All real-time monitoring of rainfall in the Agency is currently performed using tipping bucket rain gauges. These instruments count rainfall amounts in increments equal to the size of the tipping bucket, which is typically in the range 0.1 to 1.0 mm. When connected to a telemetry system, the instrument can be set up for event based reporting following each 'tip', or to report accumulations over equal intervals in time (e.g. 15 minutes).

2.1.2 Installation

The problems with measuring rainfall by tipping bucket rain gauges are well known and measurements can be affected by the exposure to local wind conditions (at the site, and at the instrument), height above the ground, the design of the instrument, snowfall, and other factors.

Advice on best practice in site selection, installation and operation can be found in Chapter 2 "Precipitation" of the Agency's Hydrometric Manual (Environment Agency, 1998a) and in the following subsections of British Standard BS7483 "Guide to the acquisition and management of meteorological precipitation data" (British Standards Institute, 1996):

Part 1. Network Design

- Section 1.1. *The user requirement for precipitation data*
- Section 1.2 *Network design and monitoring*

Part 2. Field practices and data management

- Section 2.1 *Technical Aspects in the field*
- Section 2.2 *Methods of observation and data tabulation*
- Section 2.3 *Data management*
- Section 2.4 *Areal rainfall*

although these documents relate to a range of possible applications for rainfall data and not specifically to flood forecasting.

For flood forecasting applications, one particular point to note regarding installation is that both the telemetry system, and the instrument, should be able to 'handle' the maximum rainfall intensities anticipated; for example, at least the 100 year storm. This can be achieved through providing back up data transmission routes and equipment, networks that can substitute for non-responding sites, and provision for on-site repairs during failures at key sites. Pit installations also require adequate drainage to avoid the gauge being submerged during intense storms. In most Agency regions, there have recently been significant improvements in the telemetry of rain gauge data, through the development of new state of the art telemetry systems. These systems provide greatly improved facilities for retrieving and displaying data, including a range of options for polling outstations, setting triggers and alarms, modern graphical displays of current and past rainfall amounts, and improved reliability of the hardware and associated software.

2.1.3 Time Resolution

For tipping bucket gauges, the time resolution which can be achieved depends on the bucket size used, and rain gauges with bucket capacities of 0.1, 0.2, 0.5 and 1.0 mm are available commercially. The Hydrometric Manual (Environment Agency, 1998a) notes that larger bucket capacity gauges (0.5 mm, 1.0 mm) are generally useful for areas of high rainfall or for flood warning where a coarser resolution is acceptable, whilst 0.1 mm and 1.0 mm bucket gauges can also be used for 'special projects'. The Manual also notes that small buckets tend to underestimate rainfall although this is not quantified. A bucket size of 0.2 mm is generally recommended for flood forecasting applications, with 0.5 mm in areas of very high rainfall intensities.

Recent research work by Chandler of University College for the Rainfall Collaboration Project (Met Office, 2001b) demonstrated that, even for quite substantial rain events, discretisation errors could be surprisingly large at short timescales, even in 0.2 mm tipping-bucket rain gauge records. The minimum timescale at which tipping-bucket rain gauge data can be regarded as adequate depends on the accuracy required in any particular application, as well as upon the type of rainfall involved. However, an analysis of a number of events, in one of the UK's best instrumented catchments, showed that data at timescales under 15 minutes may be unreliable, even for quite substantial rain events. The study proposed the following guidelines:

- For detailed study of extreme events (e.g. more than 10 mm in two hours) tipping-bucket data may be considered as reliable at timescales down to 5 minutes, but
- As a general rule, an accumulation time of 15 minutes is suggested as the minimum timescale for tipping bucket gauge data.
- For applications where accurate representation of rainfall is critical, a minimum accumulation timescale of 30 minutes is proposed, with hourly data usually providing a good estimate of rainfall profiles.

Chandler noted the last point to be particularly relevant to applications where rain gauge data might be used to adjust other measurements, such as radar rainfall estimates (refer to Section 2.2.3). The implication is that any adjustment procedure which fails to account for the discretisation in tipping-bucket rain gauge data is likely to be unreliable at timescales under 30 minutes – this has potentially very significant implications for real-time and post-processing adjustment of radar rainfall estimates.

For most current Agency flood forecasting applications, models typically run on an hourly basis, or at the standard telemetry reporting interval for river level data of 15 minutes. Generally, a 5 or 15 minute interval will be required to adequately resolve convective rainfall events (e.g. thunderstorms) which may have total durations of less than an hour, whilst longer intervals may be satisfactory for sampling prolonged frontal events.

2.1.4 Spatial Resolution

Rain gauges only provide a point value for rainfall and rainfall runoff models generally require an estimated for the total rainfall at an appropriate interval in the catchment above the forecasting point. This can be estimated from point rainfall values using:

- A single representative rain gauge
- A weighted average of rain gauge measurements (fixed weights)
- A fitted surface to rain gauge measurements (variable weights)

It is important that the same estimation technique is used operationally as in the original model calibration in order to avoid any bias in the resulting flow forecasts.

Estimates will generally improve with an increasing density of rain gauges and by locating rain gauges in those parts of the catchment which generate the highest rainfall (e.g. at high elevation). However, in low lying areas, and other areas with no appreciable spatial variation in rainfall, a roughly uniform grid distribution of gauges may be suitable.

For a given catchment, an understanding of the areal distribution of rainfall during flood events can be obtained from radar images, telemetered rain gauges, analysis of daily rain gauge records after the event, analyses of extreme rainfall using the Flood Estimation Handbook/Flood Studies Report, and the local knowledge of Agency and Met Office staff.

At least one gauge should be located in each subcatchment containing significant areas at risk, and in critical locations it may be advisable to install at least two rain gauges in each homogenous area to provide backup in case of instrumentation or telemetry failures and to identify any systematic bias arising at any single gauge (e.g. due to poor siting, calibration problems).

Telemetered rain gauges in adjacent catchments may also be useful in obtaining:

- Advance warning of incoming rainfall
- Improved area average rainfall estimates for a catchment
- Information on rainfall in remote (e.g. high elevation) parts of the catchment

Within the Agency, the arithmetic mean and Thiessen polygon approaches are the most widely used for deriving estimates of areal rainfall in real time or for post event analyses. Table 2.1 lists some of the characteristics of these and some other possible approaches (Creutin and Obled, 1982; British Standards Institute, 1996).

Table 2.1. Characteristics of some common rain gauge area averaging approaches

Method	Method	Main disadvantages
Single rain gauge	Select a single rain gauge as representative of the catchment	Except for very small catchments , probably will not capture the spatial variations in rainfall and may miss some events
Arithmetic mean	Take the average value for all rain gauges in an area (or some subset)	Gives equal weight to all rain gauges irrespective of their spacing and the rainfall distribution in the catchment.
Thiessen weighting (or ‘nearest neighbour’ method)	Derive area-based weights for ‘polygons’ around each gauge by drawing lines connecting each gauge to its neighbours, then drawing the bisectors to each line to obtain the vertices of the polygons	The implied rainfall distribution has unrealistic ‘steps’ at the boundary of each polygon The weighting factors are fixed for all rainfall events unlike the next two methods
Weighted average	Compute a weighted average value for all rain gauges in an area (or some subset), estimating the weights qualitatively based on factors such as raingauge spacing, topography, aspect, runoff, soil type etc	Has inbuilt fixed assumptions about the rainfall and runoff distribution which may not correspond to a given event in real time
Isohyetal methods	Qualitative interpolation for lines of equal rainfall from point values	Subjective and difficult to automate for real time use
Triangular planes	Construct a surface constructed of the triangular planes connecting the observed rainfall totals at each rain gauge to the values for its two nearest neighbours	Cannot extrapolate for rainfall higher than that observed at any of the rain gauges used (true for many of these methods)
More complex surface fitting algorithms (e.g. geostatistical approaches)	As for triangular planes but fitting functions which are an inverse function of gauge separation (inverse distance method), polynomial functions of separation (local best fit method), or other distance based weighting (e.g. kriging), possibly including a rainfall elevation relationship (e.g. via co-kriging)	More computationally complex and should provide better results, but can introduce unrealistic behaviour if not correctly implemented (e.g. oscillations, unrealistic extrapolations at boundaries)

Analyses may be performed in terms of absolute values, or in terms of values scaled by some representative value such as the annual rainfall at the gauge, in order to help reduce the influence of siting, elevation and other factors.

The methods are presented in approximately increasing order of complexity and accuracy but, for short duration, intense rainfall events (e.g. thunderstorms) it is unlikely that even the most sophisticated techniques can provide great accuracy, and weather radar may provide more useful estimates. Also, for all methods, the accuracy for a given catchment depends partly on the distribution of rain gauges rather than purely on meteorological considerations.

In regions and/or situations where there is little spatial variation in flood generating rainfall (e.g. frontal events in low lying areas), the Thiessen polygon method provides a reasonable compromise between accuracy and computational simplicity.

Where spatial variations are significant (e.g. in convective events and/or where topographic influences are significant), more complex methods may be used; for example a multi-quadratic fitting method has been used operationally with radar data in Thames region since the early 1990s.

Recent research (e.g. Goodvaerts, 2000, Met Office, 2001b) has also confirmed the earlier findings of Creutin and Obled (1982) that, in mountainous areas, geostatistical approaches which incorporate elevation into the spatial interpolation method (e.g. co-kriging) can provide significant improvements over traditional inverse square distance or Thiessen polygon methods.

2.1.5 Technological Advances

Although tipping buckets are relatively recent technology, further advances have been made in the last couple of decades for improved continuous monitoring of rainfall. The most signifncant development has been the development of drop-counting rain gauges.

Stow (1993) describes the ‘Hydra gauge’ – a drop-counting gauge developed at the University of Auckland in New Zealand. The Hydra gauge is solid state (no moving parts), has a potential resolution of 1/168 mm depth, a 15 second time resolution and is capable of measuring rainfall intensties of up to 200 mm per hour.

Drop counting rain gauges, including the Hydra gauge, were utilised in the recent HYREX (1993-97) radar research project (Cluckie *et al*, 2000) and an operational network of drop counting gauges is currently being installed in New Zealand in substantial numbers, as part of the routine monitoring network.

2.1.6 Rainfall Alarms

Most telemetry systems provide for alarm handling and enunciation so that a warning is provided if rainfall exceeds a given amount in a given period (e.g. 25 mm in 6 hours). These alarms are used to alert flood warning staff to potential flooding conditions and in initiating more frequent runs of Real Time Models.

Rainfall alarms should be set at values based on analysis of historical rainfall and flow records and the expected catchment response, possibly for assumed catchment conditions e.g. saturated. For example, the critical rainfall in a six hour period above which a 100 year flood is expected at a given Flood Warning Area at a given time of year (e.g. winter). It may be advisable to reduce the alarm level to provide a contingency/earlier warnings of extreme events, and to provide operational staff with an indication of how the event relates to previous events e.g. “an Easter 1998 type storm for this catchment”.

Rainfall alarms can also be used as input to the decision making process in issuing ‘Flood Watch’ conditions. Typically, simple thresholding approaches are used incorporating relationships between soil moisture deficit and rainfall event depth and duration. These are generally in the form of simple lookup tables. Simpler rules of thumb may also be used; for example, if rainfall exceeds a given amount in a given interval, initiate flood warning procedures.

2.1.7 National Tipping Bucket Rain Gauge Network

A detailed review of the national rain gauge networks operated by the Met Office and Agency was recently undertaken, as part of the Rainfall Collaboration Project (Met Office, 2001b). Some of the key findings, relating to tipping bucket rain gauges are presented in the following section. It should be noted that the analysis was undertaken using data obtained in mid-2000 and a number of regions have since seen a significant improvement in coverage due to gauges installed as part of the Easter 1998 Flood Actions initiated by the Bye Report (Environment Agency, 1998b) and additional telemetered data is becoming available from Met Office raingauges through the Rainfall Collaboration Project.

The review identified a total of 1,282 are tipping bucket gauges, of which 1,015 were operated by the Agency (at an average density of approximately 149 km^2/gauge). Approximately 15% of England and Wales lies within 2.5 km range of a tipping bucket rain gauge, with 47% falling within 5.0 km and 75% falling within 7.5 km. A regional breakdown of the Agency network is presented in Table 2.2.

Table 2.2. Environment Agency tipping bucket network characteristics (Source: Met Office, 2001b and (*in italics*) National Flood Forecasting Modelling System Strategy - Environment Agency, 2001c)

Region	Area (km^2)	Number of Gauges	Bucket size (mm) (where known)			Recording method (where known)		Network density	
			0.2	0.5	1.0	Telemetry	Loggers	Density (km^2/gauge)	Spacing (km)
Anglian	26,740	173	-	-	-	27	29	155	12
Midlands	21,860	101	0	101	0	-	-	216	15
North-East	22,490	80	80	0	0	43	20	281	17
North-West	14,430	144	132	11	0	77	67	100	10
Southern	10,960	121	121	0	0	58	62	91	9
South-West	20,310	121	53	28	23	*121*	-	168	13
Thames	12,860	*110*	*110*	*0*	*0*	*70*	*40*	117	11
Wales	21,090	167	151	16	0	131	36	126	11

Note: Breakdown of bucket sizes for Anglian region and of telemetered/logged gauges in Midlands was not known

Regional and inter-regional variations in the gauge networks were also analysed at the catchment scale. The analysis revealed a clear divide between regions with high inter-regional variations in the gauge networks and those with relatively low inter-regional variations. For tipping bucket gauges (Figure 2.1), the regions fell into three distinct groupings. The largest variations in network density being in the North-East and Anglian regions and the lowest variations in network density were found to be in Southern, Wales and the North-West.

An analysis of the topographic representation of the gauge networks revealed problems at higher elevations. At a national level, the tipping bucket gauge network is under-represented at elevations exceeding 350 m. This has particular significance for flood forecasting applications, since the main flood generating areas in a catchment are often in the highest parts of the catchment. Whilst some 2% of the area of England and Wales is above 450 m elevation, there are only nine tipping bucket gauges located above this height (0.7% of all tipping bucket gauges) with only one above 600 m, and none at all above 850 m. The Anglian region is the only region to exhibit under-representation at low elevations, the tipping bucket network being under-represented at elevations below 50 m.

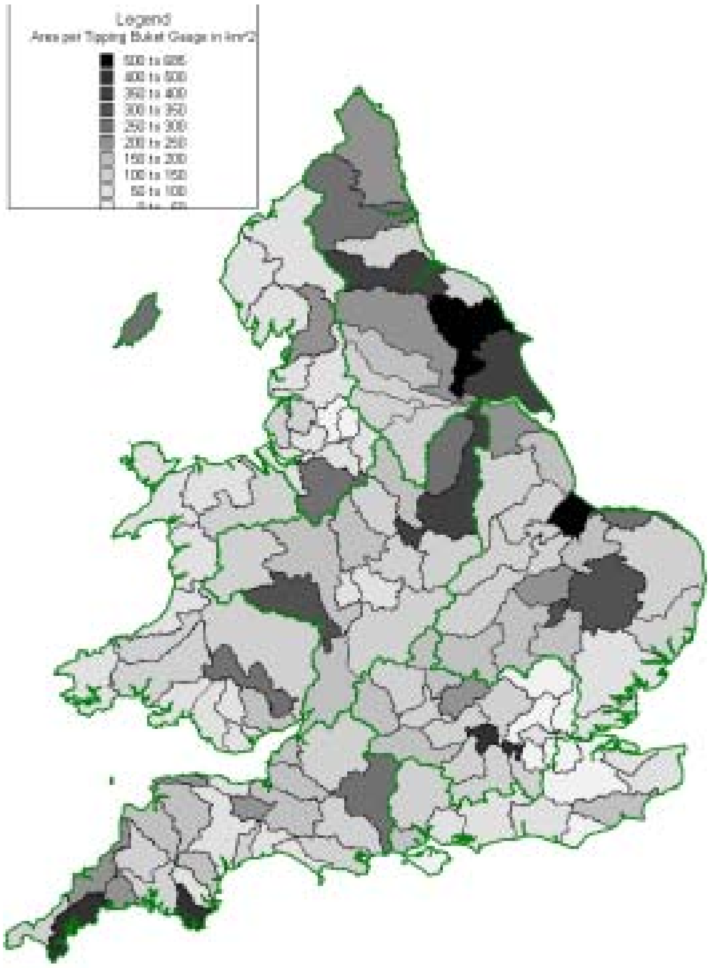


Figure 2-1. National tipping bucket rain gauge network density

2.2 Weather Radar

2.2.1 Background

Weather radars are capable of providing high spatial and temporal resolution estimates of rainfall over a wide area, in real-time from a central location. As such, weather radar has possesses considerable potential for real-time flood forecasting.

As electromagnetic waves propagate through the atmosphere they interact with raindrops, snowflakes, and hail (so-called “hydrometeors”). Weather radar exploits this interaction to infer rainfall intensities from the power of the back-scattered energy. The radar signal is pulsed so that, during the receiving phase, the distance of objects from the radar can be inferred from the time of travel of the reflected signal. Real time software interprets the signal to identify the contribution from hydrometeors, and to perform various correction techniques which are described later. Theoretical relationships are used to relate reflected power to the rainfall drop size distribution and so to rainfall intensity. Further detail on radar theory is provided in Appendix B.

2.2.2 Sources of Error

Radar is a remote sensing technique, rainfall intensities being inferred from the power of energy back-scattered from hydrometeors. The estimation process is therefore subject to considerable uncertainty. Factors which can affect the accuracy of weather radar-based products include (Figure 2.2):

- Overshooting of precipitation by the beam at long ranges
- Low-level orographic and other growth, drift or evaporation of rainfall below the radar beam
- Intersection by the radar beam of the melting layer in which snow flakes acquire a layer of melted water enhancing reflectivity (the so-called 'bright-band')
- Attenuation of the radar beam as it passes through precipitation leading to a reduction in the reflected energy
- Distortion of the beam due to strong gradients in temperature and moisture at low levels leading to the beam intersecting the ground causing false returns of precipitation (so-called 'anomalous propagation' or 'anaprop')
- Any remaining anomalous echoes due to hills and other ground clutter
- Occultation (hiding) of the radar beam(s) due to topography

Generally, anaprop problems are only a major factor in thunderstorm rainfall, whilst ground clutter and other anomalous echoes can be removed with suitable data processing. Bright band effects are most prevalent in frontal events in winter. Range dependent problems are of course a function of the distribution of radars within the network and can only be overcome through additional installations.

Internationally, there are several different radar technologies and operational options available and Table 2.3 summarises the main options which are used.

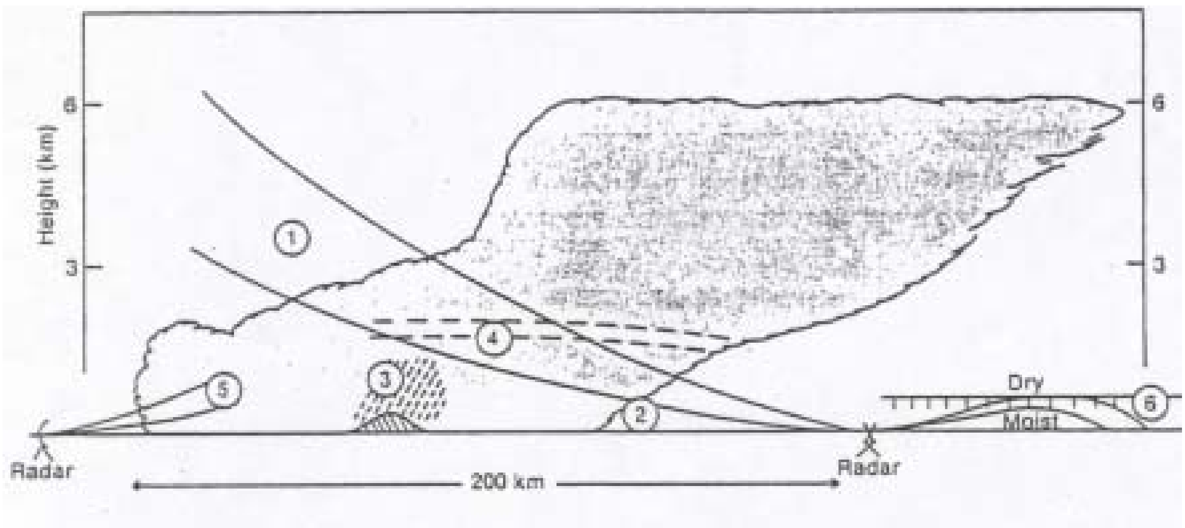


Figure 2.2. Main sources of error in radar-based precipitation measurement (Collier, 1996)

(1 = radar beam overshooting shallow precipitation at long ranges, 2 = low level evaporation below the radar beam, 3 = orographic enhancement above hills which goes undetected, 4 = the bright band, 5 = underestimation of the intensity of drizzle because of the absence of large droplets, 6 = anomalous propogation due to a strong temperature/humidity gradient)

Table 2.3. Summary of weather radar technologies and operational options

Technical Option	Comments
Operating wavelength	Radar wavelengths are identified by the following codes in order of decreasing frequency and increasing wavelength: X-band, C-band, S-band. Attenuation by rainfall and atmospheric gases is inversely proportional to wavelength: X-band radars can be severely affected whilst S-band radars are least affected by heavy rainfall but require larger antennae dishes etc so are more expensive. C-band is used in most new radar installations in mid latitude countries where they represent a good compromise between cost and accuracy
Multiple beams	Multiple beams help in making corrections based on the vertical variations in atmospheric conditions (via the vertical profile of reflectivity from atmospheric models and/or estimated directly from the multibeam radar data).
Dual Polarisation	Dual polarised radars transmit and receive radiation with horizontal/vertical polarisation helping to differentiate between solid and liquid precipitation and in estimating the size, shape and fall mode of precipitation (since larger drops deform giving different reflectivity in vertical/horizontal planes). This avoids the need to assume a uniform drop size distribution in signal processing.
Doppler capability	Doppler radar provides a reliable means of filtering stationary echoes thereby helping to correct for ground clutter and providing estimates for the wind field (speed/direction) for inputs to (or verification of) Numerical Weather Prediction models, particularly for convective storms
Beam elevation	The range of beam elevations affects the range of heights of precipitation which can be detected at any given distance from the radar. Note that, even at zero elevation, effects due to the curvature of the earth become significant beyond about 100km, with the beam height about 600m at this range.

2.2.3 National Radar Network

The national weather radar network (see Figure 2.3) has undergone significant development since the first unmanned operational weather radar was commissioned at Hameldon Hill in 1975 and there are now fifteen network radars in the UK and Eire[1]. The network is owned by a consortium of government Agencies with the Met Office providing operational support.

Until recently, radar data have had a maximum spatial resolution of 2 km x 2 km within 75 km of each radar site, and 5 km x 5 km to 210 km range. However, recent developments in the processing of the radar data (described later in this section) have led to enhanced resolution and extended range as follows, for all sites:

- 1 km x 1 km data will be available to a range of 50 km from each radar site,
- 2 km x 2 km grid to 100 km range,
- 5 km x 5 km to 250 km range.

Figure 2.4 illustrates the spatial resolution which can be obtained at a 1 km grid scale during a thunderstorm event whilst Figure 2.5 gives an example of the appearance of radar images at these three different scales.

A number of radar-based products (e.g. Nimrod; see Section 4.1) now also routinely include radar data from Northern France, Belgium and Holland to supplement the national radar network (especially to assist the tracking of thunderstorms from France and the North Sea). In operational use, at any given location, the network 'composite' image is derived from the radar with the lowest (unoccluded) beam at that location.

[1] Seven in England, one in Wales, three in Scotland, one in the Channel Islands, one in Northern Ireland, and two in Eire

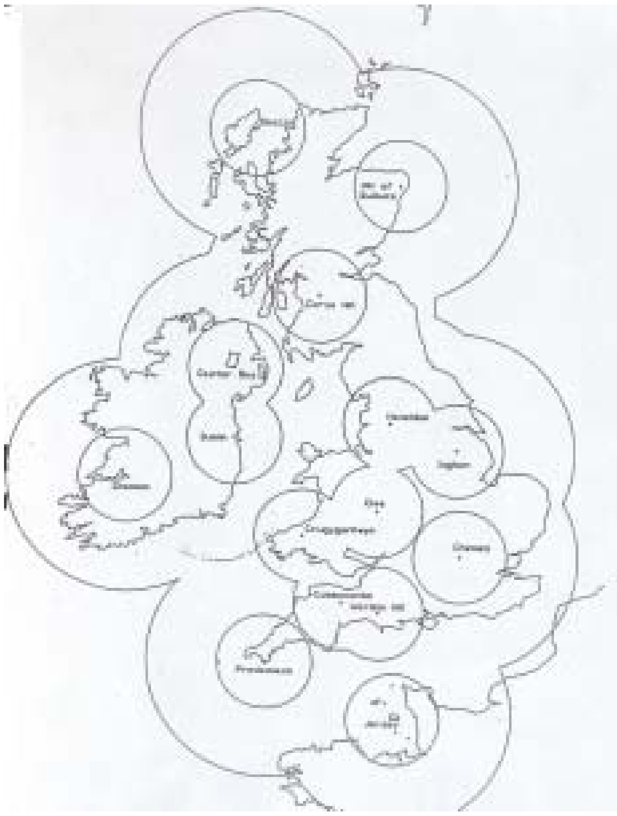


Figure 2.3. The Met Office's current UK and Eire weather radar network (Circles correspond to 75 and 210 km range from radars respectively)

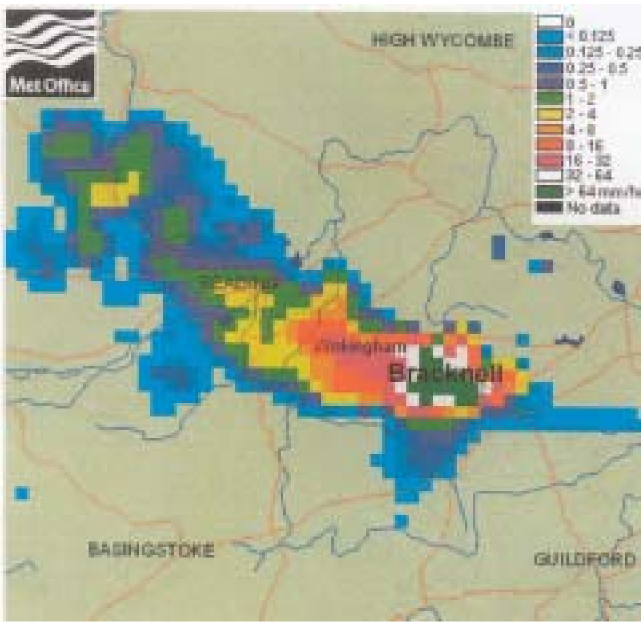
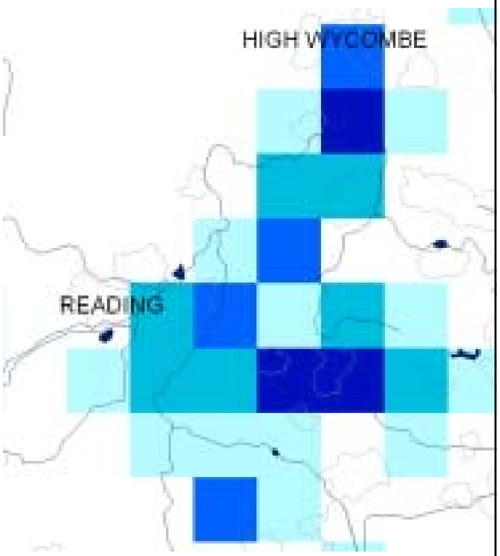
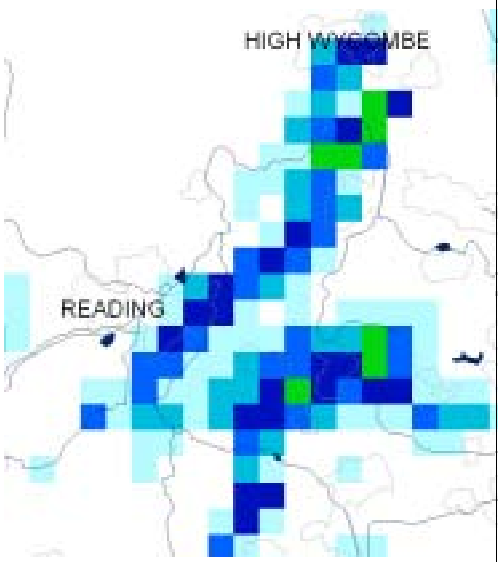
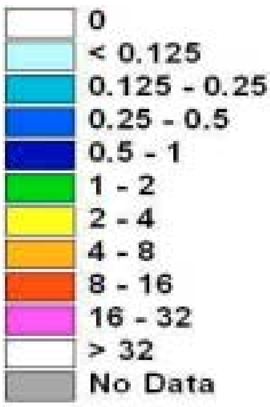


Figure 2.4. High resolution (1 km) radar imagery for 1930 GMT on 7 May 2000; from a recent storm event over Bracknell, southeast England in which 70-80mm of rainfall fell in just over one hour and resulted in localised flooding of some 300 properties (from inside cover of Weather Magazine, February 2002)

a) 5km resolution data	b) 2km resolution data
	
c) 1km resolution data	d) Key for rainfall rates (mm/hr)
	

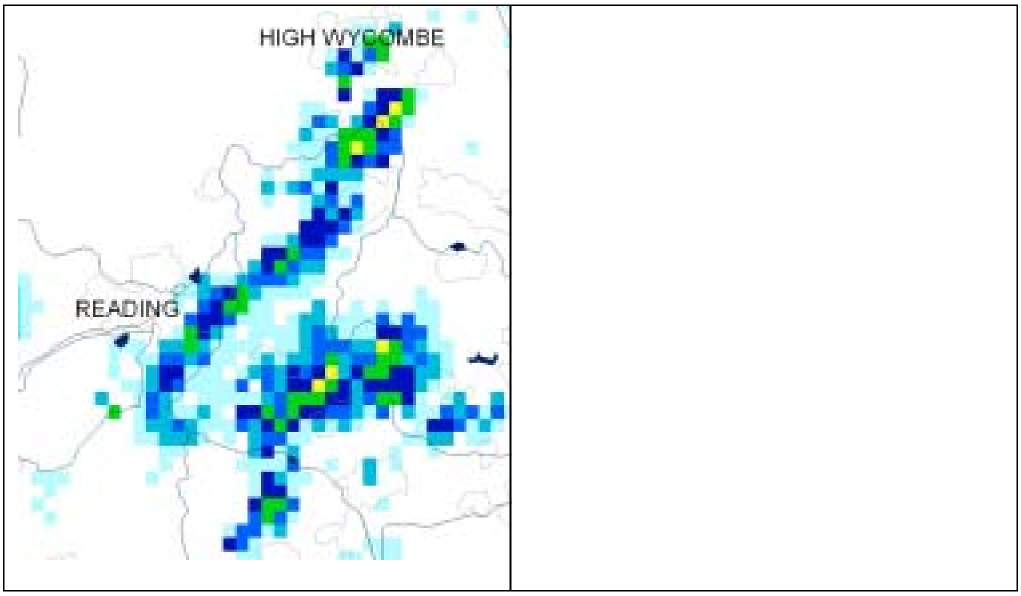


Figure 2.5. Example of radar images at different horizontal resolutions – Chenies radar, 15th Sept 1999 at 1800UTC (source: Dawn Harrison, Met Office)

A Met Office weather radar installation typically consists of a rotating 3.7m antenna dish and transmitting array housed inside a protective 'radome' (see report cover photo – of the Chenies radar). All the Met Office radars currently scan at four elevations (angles to the horizontal) and have a beam width of 1 degree. This beam width places a limitation on the maximum spatial resolution obtainable since it exceeds 1 km at about 57 km from the radar.

The lowest elevation scan for most radars is 0.5 degrees but in future may be reduced to 0.0 degrees at some sites. All network radars are single polarised and operate at C-band wavelength and two have a Doppler capability (doppler radar provides a reliable means of filtering stationary echoes thereby helping to correct for ground clutter). In addition to the Met Office network radars, the Rutherford Appleton Laboratory (funded by the Engineering and Physical Sciences Research Council; EPSRC) operates a research radar located at Chilbolton between Andover and Winchester. The Chilbolton radar operates at the S-band wavelength and is the world's largest steerable meteorological radar. Radar wavebands are fully explained in Section B3 and Table B1 of Appendix B.

The most recent installation was at Cobbacombe Cross in Devon in 1995. However, the signing of a joint Memorandum of Understanding between the Agency and the Met Office in 1998 marked a move from regional management of the network to a more strategic national footing. Funds have also been secured to embark on a programme of network enhancements designed to meet the needs of both organisations over the next ten years (but see following paragraph) (Environment Agency, 2000a). It is noted that in September 2001, the Agency agreed in principle to a new weather radar to be located in south-east England. It is proposed that this radar will be a 'hybrid-polarisation'[2] C-band device and will serve a dual research and operational role. It is expected that a further installation in north-east England will follow.

Table 2.4. Some key dates in development of the UK's national weather radar network

Decade	Development

[2] One option under active consideration is to transmit radiation polarised at 45 degrees with reflected energy components being resolved in two channels (vertical and horizontal). Whilst this configuration compromises true dual polarisation functionality (whereby transmissions are made e.g. vertically and horizontally), it does overcome operational problems associated with transmission switching.

1970-79	- Dee Weather Radar R&D Project (1969-76) - First operational unmanned C-band weather radar installed in Dee catchment (1975-76) - Dee research radar relocated to Clee Hill (1979)
1980-89	- North West Weather Radar R&D Project (1977-85) - London Weather Radar Forecasting Study (and HYRAD) (1987-on)
1990-99	- Most recent UK radar installed at Cobbacombe Cross (1995) - HYREX R&D project (1993-97)
2000-02	- Cyclops radar signal processing software introduced at all UK radar sites (2001-02) - Met Office begins taking real time rain gauge data from the Agency (2002) for pilot areas - National Interim Weather Radar Display System (NIWRDS) released (2002)

As the radar network has developed, significant technical improvements have been made in radar system performance (especially sensitivity and stability), and in the computer processing of data and data communications. The main recent development, which became fully operational at all sites in 2002, is a new Met Office radar control and data processing software package called 'Cyclops' which offers the following improvements:

- faster data processing
- the transfer of polar format data (1 degree by 750 m) from each radar site to Bracknell
- the introduction of higher spatial resolution (1 km) data and the extension of the ranges of 2 km and 5 km data respectively as discussed above

Further improvements in radar data quality will soon be realised from the following additional planned developments:

- to improve the signal noise ratio (by increasing the number of pulses processed by the software)
- to incorporate a statistical ground clutter filter which will set a 'probability of clutter' filter parameter in the data which will be used in central processing
- to support a move to a 0.0 degree beam elevation at several radars (due to improved ground clutter removal)
- to improve rain gauge adjustment techniques

Regarding rain gauge adjustment techniques, it should be noted that, although it is widely believed that weather radar measurements are adjusted in real time by the Met Office, in fact in recent years this adjustment has only occured on a weekly basis and was aimed mainly at removing any systematic bias in radar measurements due to hardware calibration errors and variations in radar sensitivity.

In this scheme, for weeks in which little rainfall has occurred, or the change in correction factor is small (not passing a significance test) or open to doubt, no correction is made. This method replaces an earlier scheme in which real time adjustment was performed at some radars using the Collier et al. approach (see National Rivers Authority, 1995) although this was removed since it was found that the Met Office's network of telemetered rain gauges was not dense enough to support such an approach, particularly during convective events.

However, improved rain gauge adjustment techniques are currently being evaluated by the Met Office; for example, a modified version of the scheme used in the USA's NEXRAD system has recently (2002) become operational (Gibson, 2000) and will be replaced with a 'Kriging with external drift' scheme once sufficient raingauge data becomes available through the Rainfall Collaboration Project. Real time rain gauge adjustments are also performed in the HYRAD system which is also used in some Agency Regions (see Section 3.4). Generally, adjustment techniques work better in situations of reasonably uniform rainfall (e.g. frontal/low level orographic) and less well in convective rainfall and when bright band effects are present.

Until recently, weather radar information was delivered to the Agency by a variety of methods. Software display systems included Microradar, STORM, MIST, REMUS and CASCADE, with other systems (HYRAD and WRIP) having a predictive capability. From 2002 all regions have also had access to the National Interim Weather Radar Display System (NIWRDS). NIWRDS will provide full access to the Met Office's Nimrod products, the facility to overlay GIS coverages on the images (e.g. rivers networks, catchment boundaries, coastlines etc), radar image archiving and replay facilities, and the option to calculate catchment average rainfalls. The system is Windows based and is implemented as a harmonised Agency desktop application, making it available (subject to licensing) over the Agency's Wide Area Network on the standard Agency desktop.

2.2.4 Current R&D activities

Although this report emphasises the use of weather radar for flood warning and forecasting, this is only one of the applications of weather radar data, and there are/have been many active research programmes underway to improve the accuracy of radar data and forecasts both within the Met Office and in research organisations in the UK and overseas.

In the UK, for example, a low cost, low power C-band research radar was operated by United Utilities and the University of Salford at Warrington, whilst the Rutherford Appleton Laboratory continue to operate the world's largest steerable meteorological radar at Chilbolton. Also, the recent NERC funded HYREX project (1993-97) was aimed specifically at investigating the performance of weather radar for hydrological applications, using data for the River Brue catchment in central southern England (Cobbacombe, Warden Hill and Chilbolton radars), and led to a number of specific proposals for future research needs (both long term and near market). Some active research areas identified during the HYREX project, and from other programmes in the UK and overseas, include:

- Improving adjustment techniques based on modelled/observed vertical profiles of reflectivity (Environment Agency, 1995)
- Using polarised radars to gain more information on attenuation, identification of hail etc
- Improving adjustment techniques using real time rain gauge data, and assessing the network density of rain gauges required in different situations (upland, urban etc)
- Re-examination of the use of higher elevation scans in radar correction
- Using Doppler wind estimates to help identify the inception of convective events in 'clear-air'
- Adjustment of radar data using path-averaged rainfall obtained from the difference in attenuation at two frequencies along a microwave path.

Some of these areas are discussed in more detail in Chapter 8.

2.3 Automatic Weather Stations

Automatic weather stations can provide real time information on climate conditions, with reporting intervals typically set at 15 minute or 1 hour intervals. The parameters monitored can include:

- Wind speed and direction
- Air temperature
- Humidity
- Solar and net radiation
- Soil temperature
- Rainfall

Most instruments will also have a tipping bucket rain gauge and so provide an additional source of real time rainfall data (if required). Air temperature measurements can also be useful for snowmelt models and for estimating the effective rainfall (i.e. total rainfall less a 'baseflow' component) for some types of rainfall runoff model.

Automatic weather station observations can also be used to provide real time estimates of actual or potential evaporation for input to soil moisture accounting models and reservoir or lake water balance models. These models typically use the Penman or Penman-Monteith equations, which require air temperature, humidity, net radiation and wind speed as inputs. Temperature, humidity, wind speed and/or radiation data may also be useful in snow melt models.

Installation considerations for automatic weather stations largely mirror those for tipping bucket rain gauges and conventional meteorological stations. The rain gauge (if used) should be installed following guidelines in the Agency's Hydrometric Manual (Environment Agency, 1998a) or BS7483 (British Standards Institute, 1996). Wind speed and direction measurements are usually made at a height of 2m above the ground, and net radiation measurements are usually made over short (mown) grass.

2.4 Snowcover and Snowmelt

The types of snow observation which are useful in Real Time Modelling include:

- Snow extent
- Snow depth
- Water equivalent depth

Recommended procedures for measuring these quantities are documented in the Agency's Hydrometric Manual (Environment Agency, 1998a) and the Met Office's "Rules for Meteorological Observers" (Met Office, 1997).

Information on snowfall extent can be obtained from aerial or satellite images, and observations on the ground. Snow depth can be measured by portable rulers/scales, snow corers, or by installing suitable marker boards at measuring locations and manually measuring current depth at the standard UK meteorological observation time of 09:00 GMT. New snowfall (i.e. in the previous day) can be detected by placing a horizontal board on top of existing snow and measuring the depth accumulated each day, before clearing the board in readiness for the next day's snowfall.

Water equivalent depth gives an indication of the potential for snowmelt, and can be measured for new snow (since 09:00 GMT) or lying snow by melting the snow captured or sampled in a suitable container (British Standards Institute, 1996).

North East Region has also experimented with the use of snow pillows, in which a butyl rubber container filled with antifreeze is connected to a water level recorder in order to measure the weight, and hence water equivalent, of accumulated snow in real time (National Rivers Authority, 1996). Installations must be at sites where snow drifting or scour will not be a major problem; for example in clearings in forests or within walled compounds. In real time operation, the main problems which can occur are 'bridging' of snow and preferential melting between the pillow and surrounding ground, both affecting the measured water equivalent of snow.

Tipping bucket rain gauges can also be used to measure snowfall through use of a thermostatically controlled low power heater inside the rain gauge to protect the bucket tipping mechanism from freezing and the precipitation from freezing within the bucket and funnel (Environment Agency, 1998a). Snowmelt measured in this fashion is not instantaneous and thus the record of rainfall duration and intensity obtained will not reflect the pattern of snowfall but only the total water equivalent of the precipitation. Drifting and evaporation can both cause errors in the water equivalent recorded.

The factsheets in the Real Time Modelling Technical Report describe some possible approaches to modelling snowmelt and an Agency sponsored R&D project (National Rivers Authority, 1996) provides a comprehensive review and assessment of the various approaches which are available.

2.5 Satellite Observations

In the UK, the main source of satellite imagery is the European Meteosat satellite, which is one of three geostationary satellites operated around the globe for weather applications on behalf of WMO. The current Meteosat satellites have three detection channels of which only the visible and infrared (IR) can be used to estimate precipitation amounts (Golding, 2000). For IR, likely rainfall intensities can be inferred from cloud top temperatures, although cloud morphology is also used to assist in the process, and to help discriminate between clouds with similar cloud top temperatures but different rainfall producing potential (such as cirrus and cumulonimbus).

Direct use of satellite imagery is limited within the Agency to qualitative applications. For example, some regions use the images to provide a general guide to the extent and progression of rainfall during flood events, and on when to give the 'All Clear' after flood events. The Met Office's Nimrod system (see Section 4.1) makes use of this limited data to help in processing radar data to decide the probability that rainfall is genuinely occurring at a point (rather than being due to anomalous echoes etc), and in extrapolating beyond the range of the current radar network.

A programme for the deployment of three new Meteosat satellites (Meteosat Second Generation - MSG) is currently underway as a joint project between the European Space Agency (ESA) and the European Organisation for the Exploitation of Meteorological Satellites (Eumetsat). MSG-1 is scheduled for launch onboard Ariane-5 from French-Guiana in mid-August 2002 with MSG-2 due to follow approximately 18 months later. The MSG satellites will significantly increase the amount of information available, through the provision of additional channels and enhanced resolution, although the ability to determine rainfall rates will remain limited (in equatorial regions, however, the existing systems have shown some promise in estimating rainfall based on cloud top temperatures). Further information on MSG, including useful website addresses is provided in Appendix G.

Research has also suggested that the microwave sensors carried on some military satellites could provide useful precipitation estimates under UK conditions, should this information ever become available in real time for civilian use.

3. RAINFALL FORECASTING TECHNIQUES

3.1 Introduction

A number of Met Office forecast products are available to the Agency from the Met Office. This section reviews the main forecast products which are currently used or under development, and gives a brief outline of the techniques used. Appendix C provides additional information on each technique described.

For flood forecasting and warning applications the main requirement is for quantitative forecasts of point and areal rainfall i.e. Quantitative Precipitation Forecasts (QPF) (although qualitative forecasts are of interest e.g. of heavy rainfall, or satellite images of cloud cover).

QPF products are operationally available to the Agency from the Met Office for very short-period forecasts (up to 6 hours - 'Nowcasts') up to longer lead-time products (up to 10 days ahead - Daily Weather Forecast; Heavy Rainfall Warning; Severe Weather Warnings). The technology underpinning these forecast products is described in the following sections.

3.2 Numerical Weather Prediction

Numerical Weather Prediction (NWP) forecasts provide the basis for many of the Met Office's forecasting products. The methods are based on a set of equations describing the dynamic, thermodynamic and conservation properties of the atmosphere.

The accuracy of surface pressure forecasts, which relates closely to the location of large scale precipitation systems has improved significantly in recent years such that five day forecasts of large scale weather systems, are now as accurate as forecasts of such systems made three days ahead twenty years ago. This means that, in some cases, qualitative forecasts of frontal precipitation can now be obtained from 3 to 5 days ahead.

The Met Office has developed a so-called unified model which combines and standardises operational NWP, long term climate modelling and ocean modelling. The model is run on a Cray supercomputer and forms the basis for many of the forecast products issued by the Met Office. For day-to-day modelling there are two atmosphere-only versions, sharing the same physical parameterisations:

(i) Global model – global coverage, run twice per day at 00:00 and 12.00 GMT out to T+144 hours.
(ii) Mesoscale model - the UK and a small part of Continental Europe.

The global model has a horizontal resolution of 0.83 degrees longitude and 0.56 degrees latitude giving an approximate resolution of 60 km in mid-latitudes. There are 30 vertical levels with humidity calculated on the lowest 27 levels. The global model is used to provide boundary conditions to the mesoscale model which is a regional model centered on the United Kingdom. This model has a resolution of 0.11 degrees latitude by 0.11 degrees which is approximately 11 km. This model has 38 levels with humidity calculated on the lowest 35 levels. The additional levels in this model are in the boundary layer to provide extra detail for forecasting over the UK.

The global model is run twice a day to produce forecasts for up to 6 days (144 hours) ahead. These main runs are initialised with data valid at 00:00 and 12:00 GMT and are started at approximately 03:05 and 15:05 GMT respectively. To enable early products to be generated, preliminary runs of the global model are also run. The preliminary model runs provide boundary conditions for the mesoscale model, which is run at data times of 00:00, 06:00, 12:00 and 18:00 GMT. The mesoscale model produces forecasts for up to 48 hours ahead.

The models predict a wide range of parameters including wind fields, temperatures, atmospheric pressures etc and hold explicit values of fractional cloud cover, together with separate values for cloud water and cloud ice mixing ratios (i.e. kg of cloud water/ice per kg of moist air within a cloud). Cloud water is converted to forecasts of precipitation by a process known as autoconversion, the rate of which increases with increasing cloud water mixing ratios. A cloud model is used to represent Cumulus and Cumulonimbus convection, in which updraft and precipitation-induced downdrafts are considered together with the types of precipitation (rain, snow, hail).

Further information on NWP is provided in Section C1 of Appendix C.

3.3 Ensemble Forecasting

NWP models provide a single 'best estimate' of future conditions based on current meteorological observations around the globe and numerical models for predicting atmospheric behaviour. Forecasts become less accurate with increasing lead time because of the growth of errors in the initial conditions, and because numerical models cannot describe the laws of physics exactly. Ensemble forecasting is a relatively recent development which is now routinely used to provide rainfall forecasts for forecast lead-times of up to 10 days using a 30 km grid scale.

Ensemble forecasts are provided by the European Centre for Medium Range Weather Forecasts (ECMWF) (Molteni *et al.*, 1996). The ECMWF's Ensemble Prediction System (EPS) provides a practical tool for estimating the uncertainty in forecast conditions and hence, the likely magnitude of forecast errors.

To do this, the Met Office global model is run for 51 member ensembles to provide forecasters with a set of 51 possible future scenarios. These can be combined into an average forecast (the ensemble-mean) or into a small number of alternative forecasts (the cluster), or kept separate so that they can be used to compute probability distributions of possible future weather conditions.

Figure 3.1 shows an example of the EPS output for a heavy rainfall event for the Piedmont area of Northern Italy, 29 October to 2 November 1994. In this example, a good indication of the likely heavy rainfall occurrence is given up to about T+7 days, although considerable uncertainty exists at this lead-time.

Ensemble forecasts play an important role in deriving the long term forecasts issued by the Met Office but are not presently available to the Agency for use in Real Time Modelling.

Further information on ensemble forecasting is provided in Section C2 of Appendix C.

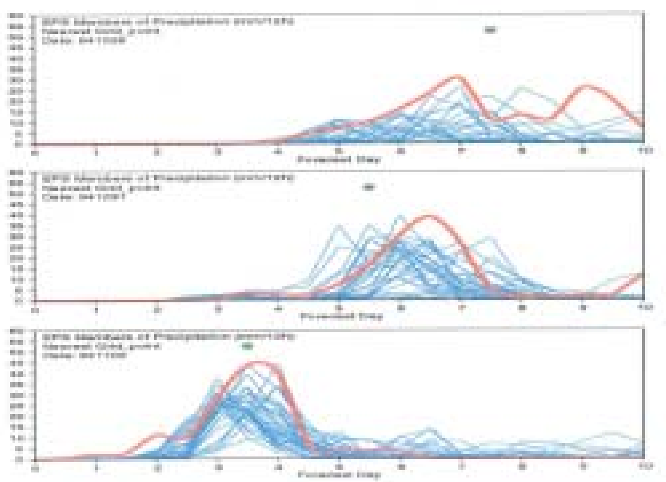


Figure 3-1. Example ensemble forecasts. The solid red line is the total precipitation given by the control model run, blue lines are the members of the ensemble showing the confidence in the control. The green mark on each panel identifies the amount of the 12 hour accumulated prediction from observations, valid for 0000 GMT, 6 November 1994 (from Petroliagis *et al.,* 1997).

3.4 Radar only techniques

In addition to NWP models, a number of simpler techniques have been developed for forecasting rainfall at short lead times by forecasting the future motion of rainfall areas based on radar observations of their current speed and direction of motion. The Met Office's Nimrod product (see Section 4.1) incorporates this technique, but two additional software products which are currently used within the Agency also include this technique using Met Office feeds from the UK radar network. These are:

- HYRAD – Used in Thames, Midlands, Anglian and North-East regions
- WRIP – Used in North-West and South-West regions

The HYRAD system (Moore *et al*, 1991, 1994a,b) builds upon work done for Thames region in the early 1990's and includes algorithms to adjust radar data using rain gauge data and to generate short-period forecasts of rainfall using 2 km grid radar data. The forecast system is based upon a simple advection model using linear extrapolation although experiments have been conducted using echo growth procedures with limited success. Using this approach a velocity inference and 2-hour or more ahead rainfall forecast is produced. A multiquadratic surface fitting scheme is used to apply the real time rain gauge corrections.

The Weather Radar Information Processor system (WRIP; Han *et al*., 1997) is currently used in South-West and North-West regions and includes a number of facilities for displaying and analysing weather radar data including the ability to replay events, and automatic storm analysis of speed and direction, with rainfall prediction. Storm motion up to six hours ahead can be forecast using a simple linear advection technique.

4. MET OFFICE PRODUCTS

4.1 Nimrod

Nimrod is the Met Office's main product for delivering radar actuals and short term rainfall and other forecasts (0-6 hours) to users (Golding, 1998; 2000). Nimrod came into operation in 1995 and replaced an earlier system called Frontiers. Nimrod is fully automated whereas Frontiers required continual intervention by the Met Office forecaster. Figure 4.1 shows an example of output from the system

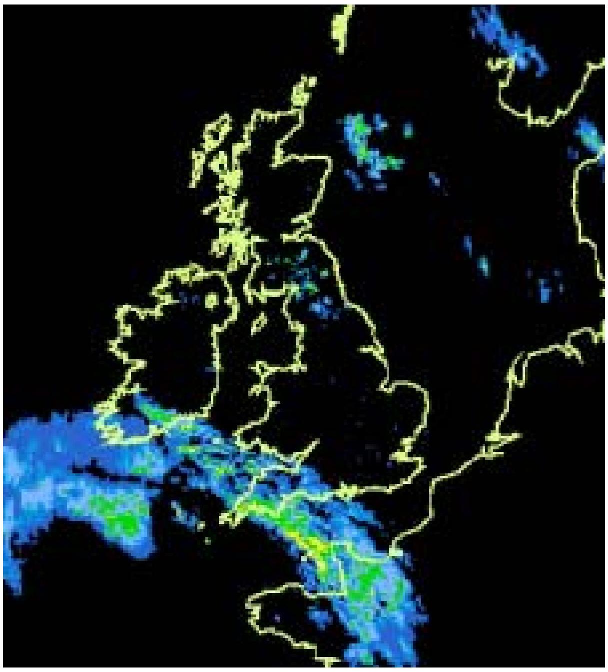


Figure 4-1. Example of Nimrod radar actual rainfall product

In real time operation (Figure 4.2), Nimrod ingests data from the weather radar network (including Irish and recently some French and Belgian radars), Meteosat satellite observations, lightning location systems, and the Met Office and some Agency rain gauges to generate as complete an observation of areal precipitation as possible. The product is available within about 15 minutes of the time of data capture, although, as described in Section 3.2, the NWP component is only updated every 6 hours.

The basic product is a corrected composite of radar rainfall data. Detailed corrections are made to obtain the best possible estimate of rainfall at the land surface and include corrections for errors in the raw radar data (such as for bright band), orographic enhancement of rain below the radar beam, overshooting by the beam at long ranges, and so on. In the absence of these corrections, errors up to a factor of ten are possible. The corrections for low level enhancement can also be large, reaching up to 10 mm/hr on some windward mountain slopes in favourable conditions (e.g. in South Wales in winter frontal rainfall).

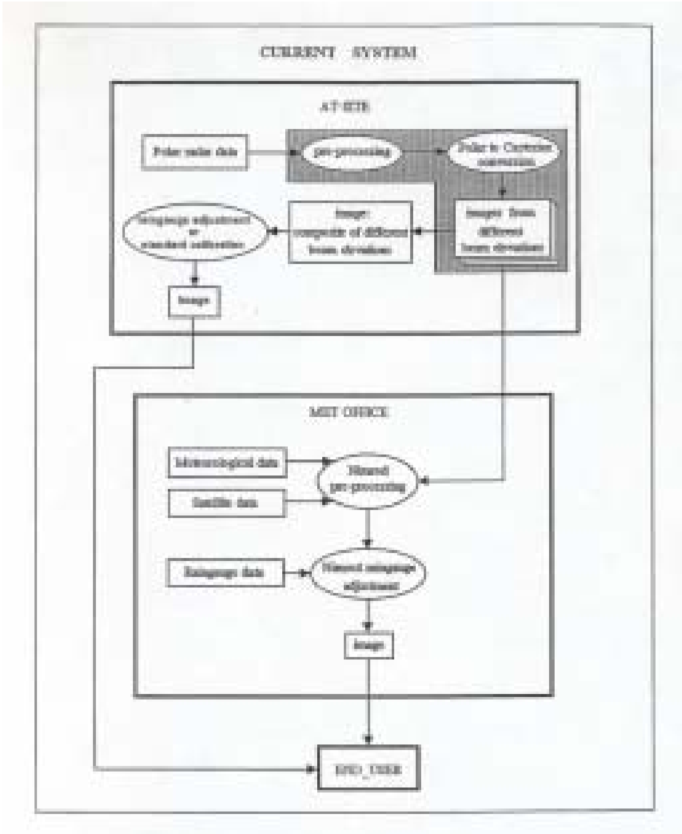


Figure 4.2. Main components in the Nimrod system (National Rivers Authority, 1995)

Nimrod also includes short term forecasts of precipitation out to 6 hours ahead. In Met Office terminology, the Nimrod estimates of current rainfall are called ‘Nimrod analyses’ (or ‘actuals’) and these are provided on a 15 minute cycle, with a 30 minute cycle for cloud, visibility and other forecasts (but 15 minute for precipitation forecasts), which are called ‘nowcasts’. Forecasts are generated from analysing the motion of rainfall areas and extending them into the future (i.e. radar-only rainfall forecasting) combined with forecasts generated by the Met Office mesoscale meteorological model.

Radar-based forecast methods typically predominate at very short lead times (up to one to two hours) with longer lead time forecasts being mainly model based. The use of models also allows Nimrod to develop or dissipate rainfall as appropriate, which is not possible using only radar-only methods. The split between radar and model based forecasts varies with lead time but the transition between these various methods is handled automatically and is not transparent to the user.

The current version of Nimrod also incorporates elements of ‘Gandolf’, a system developed to deliver improved forecasts of short lived convective storms (e.g. thunderstorms) although for the present Gandolf also remains a separate product. The Gandolf Thunderstorm Warning Project (Environment Agency, 1997) ran from 1994 to 1997 and was initiated by Thames region which had identified thunderstorms as a major cause of flooding in urban catchments. Further information on the Gandolf system may be found in Hand, 1996; Pierce *et al*., 2000 and Golding, 2000).

Within Nimrod, the technique used is to assess whether convective storms are present using a combination of radar and satellite information to classify cloud structures as convective or not. If convection is diagnosed, radar observations and mesoscale model estimates at a number of heights are used to determine the current stage of development and the potential future development of the convective cell. A conceptual (‘life-cycle’) model of the development of convective storms is used to predict how a storm’s development will proceed from the time of detection. However, the development of convective storms may be so rapid that it can be difficult for useful forecasts to be issued in advance. Section 5.5 reports preliminary findings from an international comparison of rainfall forecasting procedures undertaken in Sydney in 2000.

The Met Office is continuing to investigate improved forecasting of convective rainfall. The Convective Diagnosis Project (CDP) has the aim of providing probabilistic forecasts of localised convective storms. The aim of the CDP is to provide, on a 2 km grid, a probabilistic indication of those areas where convection can be considered more likely when the overall atmospheric conditions are favourable for storm generation. The CDP uses mesoscale model outputs along with knowledge of topography and land use and condition to identify areas where uplift may be forced from the surface. This has been seen as the way forward in the absence of a means of locating areas of converging air and atmospheric ascent directly (e.g. from doppler radar observations). Further information on CDP is presented by Hand (1999).

For Nimrod, the he overall concept is to produce a 'seamless' forecasting system that defaults to the most appropriate subsystem by diagnosing atmospheric conditions. The total system will use Nimrod as a default and the new CDP diagnosis system when seen to be successful. There will not be separate systems producing different products and therefore there should be no confusion over which product to use. However future users of the output from this new system would need to be aware of how the system works, what products they are receiving, how they are derived and the confidence the meteorologists have in the accuracy those products. This topic is covered further under Forecaster Training in Section 7.2.2.

4.2 Heavy Rainfall Warnings/Daily Rainfall Forecasts

Heavy Rainfall Warnings are based on a combination of Nimrod (previous section), NWP (Section 3.2) and ECMWF (Section 3.3) outputs and the experience of Met Office forecasters. They are typically issued for times 6-24 hours ahead. Daily Rainfall Forecasts are also generated using similar techniques and cover 24 hour accumulations (or sub periods) over general areas (e.g. North Wales, Severn Lowlands) for up to 4 days ahead.

At longer lead times, global and ensemble models, with their relatively coarse spatial and temporal resolution, play a larger role in the forecasts, since the incoming frontal and other systems may initially lie outside the domain (i.e. extent) of the mesoscale model at the start of the forecast. This means that rainfall forecasts are only applicable for wider areas and for longer time periods than the shorter term Nimrod forecasts.

Both types of forecast are issued to Agency Regional Control Centres by the local Met Office Civil Centres. Other longer term forecasts (e.g. Severe Weather Warnings, Flash Warnings) do not specifically concern rainfall so are not discussed in these guidelines; however, these are issued directly from the Met Office's headquarters in Bracknell.

There is no standard national format for Heavy Rainfall Warnings but the product typically contains information on:

- Date and time of issue of a forecast, and its validity
- Quantity of rainfall
- Period during which rainfall is expected
- Maximum rainfall intensity or period of peak rainfall activity

Table 4.1 lists the Heavy Rainfall Warning criteria currently used within the Agency regions.

Table 4.1. Heavy Rainfall Warning criteria used in the Agency (Environment Agency, 2001b)

Region	Number of warning areas	Criterion
Anglian	3	20mm or more in any 24 hour period 15mm or more in any 3 hour period Updates 15-25mm, 25-45mm, 40mm or more in any 24 hour period
Midlands	8	Rainfall quantities/intensities to be defined 6 hours in advance
North-East	7	General – 15mm or more in 12 hours or less Localised rain – 25mm or more in 12 hours or less
North-West	3+15	Type A – Point maxima 30-40mm or more in 6-12 hours Type B – Point maxima 15mm or more in 6 hours Type C – Point maxima 10mm or more in 6 hours Thunderstorm – 10mm or more in 60 minutes (including time of issue, period of validity, confidence 30/60/90%)
Southern	3 + 21 Flood Watch catchments	10-20mm in 4 hours, 20-30mm in 24 hours (depending on area)
South-West	2	General – 25mm or more in 24 hours or less Area specific – 10mm or more in 12 hours or less, 5mm/hr or more (including expected total rainfall, spatial variability, start and end time, type of rainfall e.g. heavy and continuous, thundery, localised)
Thames	3	Showers – 8mm/hr or more; 10mm or more in 6 hours or less Frontal – 4mm/hr or more; 20mm or more in 12 hours or less (April-Sept), 15mm in 12 hours or less (Oct-Mar)
Wales	3	25mm in 6 hours or less (except 15 mm in 6 hours or less for the Dee catchment)

Heavy Rainfall Warnings are issued using a range of procedures. One system used by Met Office forecasters (Environment Agency, 2001b) has the following features:

- Derives rain accumulations from Nimrod rain rate analyses and/or Nimrod rain accumulation forecasts
- Uses different warning thresholds for different warning areas/catchments
- Produces warnings for the areas defined by the Agency for their Heavy Rainfall Warnings
- Produces warnings for UK Regions using the criteria defined by the National Severe Weather Warning Service
- Produces text warning messages to Civil Centres to alert forecasters that some "event" has occurred/will occur and to look for further information on a Met Office web site

The current Met Office procedures for issuing Heavy Rainfall Warnings are labour intensive and a Met Office R&D programme is underway to help to automate these procedures at lead times from 0-6 hours (Driscoll *et al*, 2000). This experimental system generates so-called 'first guess' warnings when the accumulated rainfall exceeds a predefined criterion (e.g. 15 mm in a three hour period in a 5 km grid square).

Also, for longer lead-times, a recent project investigated the application of ensemble predictions of high rainfall events to generation of automated input to the issue of early warnings (Environment Agency, 2001b). The resulting system identifies extreme situations from the ECMWF and other ensemble data, then constructs a first guess warning message using the Met Office's Nimbus forecaster support system which can be then modified and issued, as appropriate, by the forecaster.

4.3 MOSES

MOSES (Met Office Surface Exchanges Scheme) is a new (2002) Met Office product providing estimates for a range of surface-related parameters across the UK on a 5km grid scale with hourly updates (Golding, 2001). MOSES is scheduled to replace an earlier system called MORECS which has a much coarser resolution (40 km grid scale, weekly updates).

The product is based on a modified version of the vegetation/ surface/ sub-surface parameterisation scheme used by the NWP Model for forecasting and climate simulation. The scheme incorporates CEH Wallingford's Probability Distributed Moisture rainfall runoff model (PDM), is called MOSES-PDM, and covers the UK and near continent. The inputs are: rainfall from a summation of the 15 minute rain rate analyses based on processed radar data, but using other data beyond acceptable radar range, and short wave radiation from a surface radiation model using hourly Nimrod cloud 3-D analyses derived from satellite imagery, incorporating surface observations.

Near surface atmosphere parameters are obtained from Nimrod, which adjusts the mesoscale NWP fields to fit observations. Vegetation is currently prescribed seasonally, as in MORECS, with a plan to switch to using satellite observations. Snowfall is determined from the Nimrod precipitation type diagnosis, which provides a snow fraction. Snowmelt is handled using a heterogeneous snowmelt model.

MOSES is potentially useful for providing estimates of antecedent conditions in the rainfall runoff models used in some flood forecasting systems, for providing estimates of snow cover and snowmelt, as well as helping in deciding whether to issue a Flood Watch (although this remains to be proven as this is a new product). A joint Met Office/Agency project is comparing the output from MOSES with that from the earlier MORECS system.

5. EXAMPLES OF INTERNATIONAL EXPERIENCE

5.1 Introduction

Within the meteorological community, the Met Office is regarded as an international centre of excellence. Considerable expertise also exists worldwide although operational procedures and research activities are strongly influenced by local climatic conditions; for example, the need to track and forecast tornadoes and hurricanes in the USA, or to forecast tropical cyclones in the Pacific region. In this report, it is only possible to briefly outline procedures in a few other countries, and in this section several examples have been picked which are particularly relevant to flood forecasting in England and Wales, including several from the proceedings of the American Meteorological Society Conference on Radar Meteorology held in Munich in July 2001. Appendix E presents the list of sessions from this conference, together with a list of papers presented at the recent NERC Town Meeting on the Science of Quantitative Precipitation Forecasting held in London in May 2001 (NERC, 2001).

It should be noted that most of the models described here are highly specialised and are generally operated by national Weather Service staff with responsibilities for operational flood forecasting.

5.2 USA/Canada

Nowcasting in the USA and Canada has sometimes followed a different path to that in Europe and the UK in particular. In North America, the emphasis for short period forecasting is on severe weather, especially tornadoes and other severe gusts, hail and lightning. However the need to increase warning times for such phenomena has given impetus to the development of a number of nowcasting systems with features that could potentially benefit the nowcasting of heavy, localised rainfall and flooding in the UK.

5.2.1 NEXRAD

Most forecasting systems in the USA rely heavily on the provision of high resolution data from the national network of S-band doppler radars. This is provided by the US National Weather Service (NWS) network of WSR-88D radars that are supported by a range of weather detection algorithms (Crum and Alberty, 1993). Along with these there are semi-operational forecasting systems (i.e. research systems installed for evaluation purposes in NWS offices). The responsibility that NWS offices have for producing flood warnings means that the potential exists for full training and application of the products available.

Other than their Doppler capability, NEXRAD radars have a multi-level scan sequence which allows greater investigation of cloud and precipitation structure than the four elevations used by the UK weather radars. This enables greater correction for the common errors in radar rainfall estimation (Vertical Profile of Reflectivity corrections), as well as determination of storm type and evolution.

The USA also has an experimental (semi-operational) system installed in a number of forecast centres called AMBER (Areal Mean Basin Estimated Rainfall). This is similar to the systems currently employed by the Agency in some of its regions in that it estimates accumulated rainfall totals over specified catchments and has the capability to ingest forecast (radar) rainfall to predict catchment accumulations. Alert triggers are set to respond when mean catchment rainfall exceeds predetermined threshold levels. Catchments on alert (or higher status) appear coloured on a map display.

A recent development of this system at the National Severe Storms Laboratory (NSSL) has been a web-based version called ‘QIWI’. This displays catchment maps (required due to forecaster unfamiliarity with the large scale and number of catchments in their region) and topography. This has added functionality in that it can display alongside pictorial images other information on catchment status such as vegetation cover and soil moisture. It is not clear how these details are updated at present. Although this system has advantages in the manner in which it uses an open system that can be accessed easily by any number of users whatever their location, it seems less adaptable than the GIS based approach. It is still at an early developmental stage. (Gourley *et al.*, 2001)

5.2.2 Autonowcaster

The Autonowcaster system (Figure 5.1) has been developed over a number of years by the USA's national meteorological research centre; the National Center for Atmospheric Research (NCAR) in Colorado. It has a wide variety of features designed to improve the detection and forecasting of thunderstorm development and motion. This includes the TITAN system (Thunderstorm identification, tracking analysis and nowcasting – Dixon and Weiner, 1993) which produces forecast tracks of thunderstorms. These can then be used to make predictions of future catchment rainfall totals in a similar manner to that employed in radar-only forecasting systems (e.g. Hyrad).

The most novel and potentially useful feature of the Autonowcaster system is the detection of convergence zones from wind fields derived from Doppler radar information. These areas of convergence are used to indicate places where storms can be expected to develop. This has lead to some improvement in the warning lead times for heavy rain and delineation of at-risk areas prior to the onset of rain.

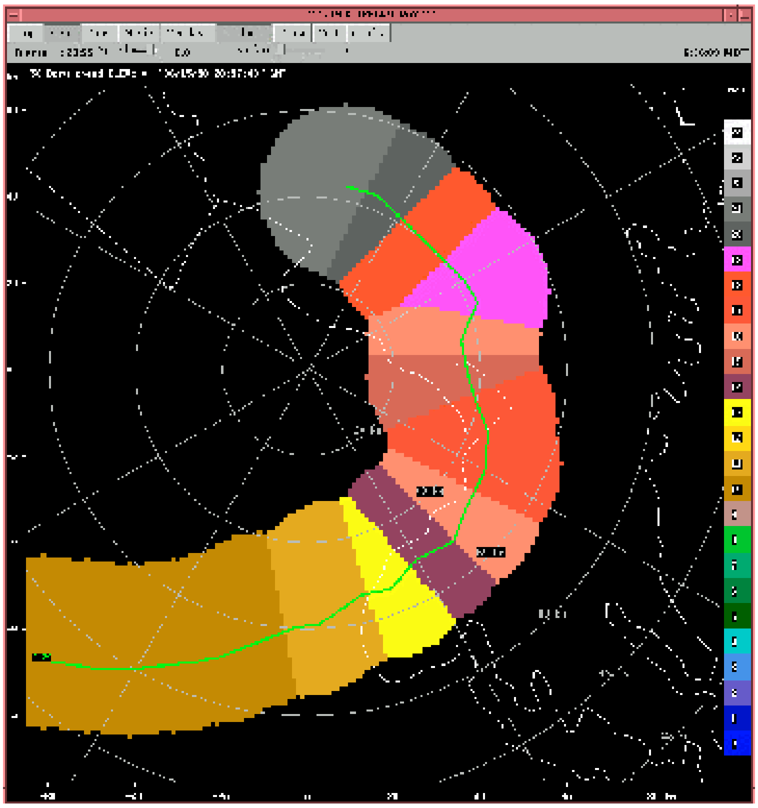


Figure 5-1. Example of Autonowcaster forecast 'lifting zone'; an area where convection is likely to be initiated by low level atmospheric convergence.

5.2.3 Warning Detection Support System

The Warning Decision Support System (WDSS) has been installed in demonstration mode at a number of NWS centres in the USA after its development at the National Severe Storms laboratory (NSSL). This has been designed as a severe weather (lightning, hail, heavy rain, downburst and tornado) warning system and does not concentrate only on flood-causing conditions (Witt *et al*, 1998). It is of interest due to its accessible and functional display, as well as the possibility to adapt a number of its products for flood forecasting purposes. Among its most notable features are the algorithms used to detect convective storm cells and determine their attributes. These include vertically integrated liquid water (VIL), presence of (severe) hail, lightning, maximum radar reflectivity and circulation type (which can be used as an indicator of storm type and potential duration in a conceptual forecast model). The cell locations and forecast tracks (Johnson *et al.,* 1993) are displayed on the pc-screen along with a table detailing each cell's attributes.

5.3 The Canadian Radar Display System (CARDS)

CARDS is the prototype Canadian Radar Display System which is currently approximately half way through a five year development period. It possesses a number of interesting features similar to those in WDSS but is not as sophisticated (as yet). In addition to these features it has a radar display that allows the user to investigate the full structure of a precipitating system by arbitrarily choosing cross-sections of the radar reflectivity image that they wish to view. This is not limited to radial scans (the classic Plan Position Indicator) and therefore allows a fuller assessment of the nature of the rainfall system by a forecaster. This is a simple to use 'point and click' function and has been incorporated into a web browser environment for easy dissemination to a number of users at different locations.

5.4 German Weather Service

The Deutscher Wetterdienst (DWD – German Weather Service) has recently (December 1999) adopted a new Numerical Weather Prediction model with special emphasis on the hydrological cycle, exchange processes at the surface and the turbulence structure of the boundary layer (Damrath *et al.*, 2000). The model comprises a global model with a high resolution regional model nested inside with a horizontal resolution of 7 km and 35 vertical layers (with 2.8 km/50 layers planned for the near future). Hourly time series of precipitation and other meteorological parameters are available to Regional Forecast Centres for estimating areal precipitation and providing Heavy Rainfall Warnings. Some examples of such warnings are daily estimates of 6 hour totals issued once per day, plus percentile values (e.g. 90% exceedance) which are issued daily for the Mulde and Spree river basins.

In Germany, DWD is also responsible for flood forecasting and use similar flood warning guidance based on rainfall forecasts; for example, a forecast of 12 mm of rain in 30 minutes or 25 mm in 6 hours can be used as the basis of a flood warning. This kind of guidance is seen as particularly important during convective storms in urban areas. For this reason radar scans are set to produce images every 5 minutes.

QPF estimates for individual grid squares are available at several flood forecast centres in Germany and are used in flood forecasting. In fast response mountainous areas such as the Alps these values are used qualitatively to provide Heavy Rainfall Warnings. Rainfall runoff models are also widely used in combination with flow routing models. The most sophisticated models include:

- The River Moselle forecasting system developed by the Federal Institute of Hydrology, which includes a hydrodynamic, statistical and rainfall runoff models, coupled directly to the output from the high resolution NWP model (rainfall, temperature etc)

- The River Neckar and Upper Rhine system which uses 120 rain gauges and outputs from the high resolution NWP model.

Additional information on recent German research into the required accuracy of rainfall forecasts and German user requirements for rainfall actuals and forecasts is presented in Section 7.3.3

5.5 International Rainfall Forecasting Inter-comparison Project

Both the Nimrod and GANDOLF systems were trialled during a major international inter-comparison experiment at the Sydney Olympics in 2000. This experiment was the first to be organised by the WMO's World Weather Research Programme.

The main participants were the Australian Bureau of Meteorology, NCAR (USA; see Section 5.2.2); Environment Canada; the UK's Met Office; and the National Severe Storm Laboratory (USA). The overall aim (Keenan *et al.*, 2001) was "to demonstrate the capability of modern forecast systems and to quantify the associated benefits in the delivery of a real time nowcast service". Emphasis was placed on 0-6 hour nowcasts from numerical weather prediction models with radar systems being the primary tool for shorter duration nowcasts (0-2 hours). The project ran for two years in the period leading up to and including the Sydney Olympics.

The operational systems operated during the experiment included WDSS (Section 5.2.3), Autonowcaster (Section 5.2.2), CARDS (Section 5.3), TITAN (Section 5.2.2), Nimrod (Section 4.1) and Gandolf (Section 4.1), with various research tools also tested (e.g. using fuzzy logic, neural networks, fractal representations). The results from these trials are still being analysed but, for example, regarding Gandolf suggested that in its current form, Gandolf forecasts of convective rainfall were only useful up to 20-40 minutes ahead under the test conditions.

Figure 5.2 shows an example of the forecast performance of the Gandolf system for a severe thunderstorm in the vicinity of Sydney. Also Grecu and Krajewski (2000) found that, in preparing very short-period forecasts, some additional benefit was obtained from considering advection processes. Neural networks were also used as part of this study but in this case were found to improve accuracy very little (i.e. programming techniques which represent the logical thought processes of human operators, albeit crudely).

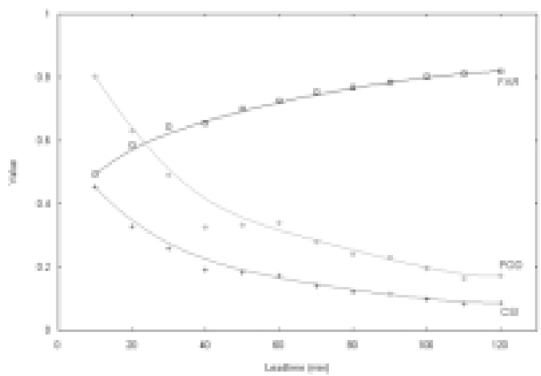


Figure 5-2. Categorical performance statistics for the GANDOLF forecasts for a supercell thunderstorm which occurred over Sydney, Australia on 3 November 2000 during the Word Weather Research Programme Sydney 2000 Forecast Demonstration Project (from Sleigh *et al.*, 2001). (The PoD, CSI and FAR statistics are fully described in Section 6.1.3, but it should be noted that the ideal scores are 1.0, 1.0 and 0.0 respectively).

6. ACCURACY OF RAINFALL MEASUREMENTS AND FORECASTS

6.1 Introduction

6.1.1 General Principles

Assessments of the accuracy of rainfall measurement and forecasts have traditionally been performed in an ad-hoc manner by Agency regions and occasionally as part of Agency R&D projects. Some regions (e.g. Midlands) also include accuracy assessments in the post event reports produced following severe flooding.

The Met Office also occasionally issues Technical Reports on the performance of its various products, together with routine monthly reports on the performance of individual weather radars and of the overall network (downtime, bias etc). However, Met Office reports are aimed at a range of users, including reports mainly for Met Office use, and are not targeted specifically at the needs of flood warning practitioners.

Several recent reviews (e.g Environment Agency, 2001b) have shown the need for a more formal approach to performance assessment and a high priority R&D project has been proposed to develop the methodologies to be used. A post event analyst has also recently (2002) been recruited jointly by the Met Office and Agency to report specifically on the performance of Met Office products in a flood forecasting context. Significant improvements in the information available should therefore be possible in the near future and this should be borne in mind when reading this description.

6.1.2 Accuracy Statistics

At present, a number of statistics are used in reporting on weather radar performance. These include measures of the accuracy in terms of total rainfall, such as the bias, and others which assess the probability of detecting rainfall at a point, such as the Probability of Detection (see Section 6.1.3).

For actual rainfall, the usual approach is either to compare individual rain gauge observations with radar values for the grid square in which the rain gauge lies, or to estimate areal accumulations from rain gauge data for comparison with radar values. For forecast rainfall, values at a given lead time can be compared with either the rain gauge or radar values which were subsequently recorded.

It is important to note that neither rain gauge or weather radar actuals can be taken as 'truth', and that these statistics simply compare two alternative and complementary estimates of rainfall, each with their own measurement difficulties. Figure 6.1 illustrates this point for the simple case of a developing thunderstorm tracking across a catchment containing three rain gauges. It can be seen that the time series of rainfall measured at each rain gauge, and the highlighted radar 'square', are very different and that no single rain gauge time series gives a correct indication of the overall catchment rainfall.

Due to these spatial and temporal sampling issues, any measures which compare radar and rain gauge data should also be qualified by the following additional information:

- The general location (and/or topography, local influences, mean rainfall etc)
- The averaging/accumulation interval (e.g. 1 hour, 1 storm event)
- The threshold value where appropriate (e.g. > 1mm)
- The lead time, if any (e.g. 1 hour)
- The spatial extent (e.g. point values, 2 km grid square, 100 sq.km. catchment)
- The number, type and magnitude of rainfall events considered (e.g. convective, frontal)

- The number of point or grid square values used in the assessment (e.g. rain gauges)
- The processing techniques used (e.g. area averaging procedures, raw/corrected data etc)
- Any instrumental problems during the event (e.g. radar downtime)
-

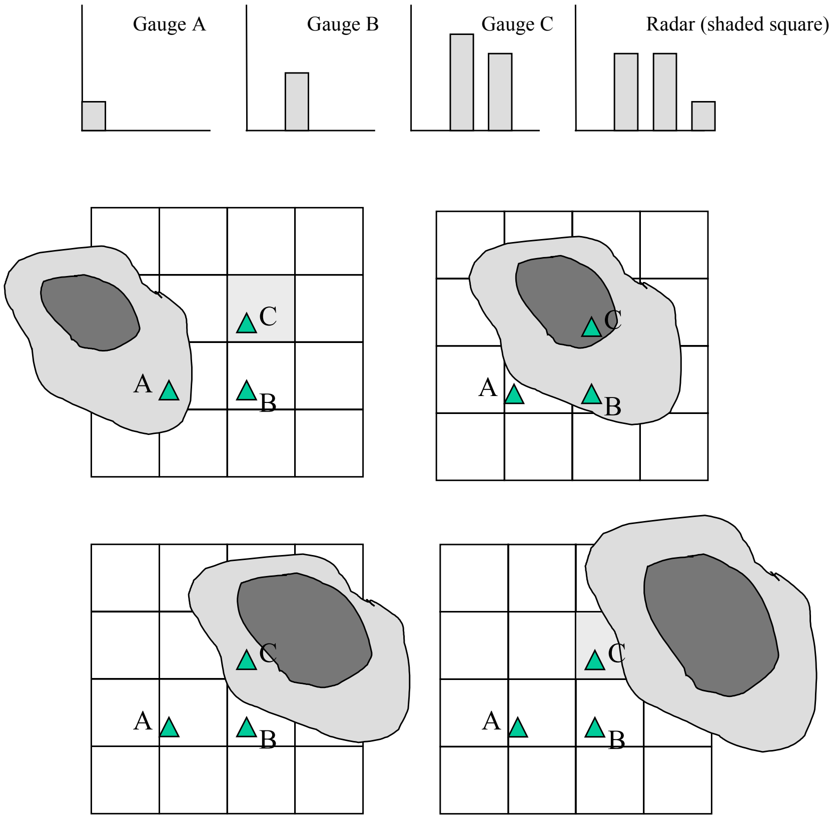


Figure 6.1. Illustration of the differences between radar and rain gauge sampling (darker shading indicates a higher intensity of rainfall)

6.1.3 Met Office Performance Statistics

The Met Office issues monthly reports on the performance of individual radars and of the network as a whole, together with occasional reports following heavy rainfall and other significant events. For example, monthly summaries are provided for each radar for raw and corrected data over ranges of distance from the nearest radar (e.g. 0-50, 50-100 km, corresponding to areas of approximately 8,000 and 24,000 km^2 respectively).

The main statistics which are used to present the accuracy in estimates of total rainfall are:

bias:

$$B = \overline{G} - \overline{R}$$

root mean squared error:

$$RMS = (\frac{1}{N}\sum e^2)^{0.5}$$

root mean squared factor:

$$RMSF = \exp\left(\frac{1}{N}\sum e_l^{\,2}\right)^{0.5}$$

where R is the radar/Nimrod value, G is the rain gauge value, $e = G - R$ is the difference between the radar/Nimrod and rain gauge values, e_l is the difference in the logarithms of these values, an overbar indicates a mean value, and N is the number of instances over which the statistic has been computed (subscripts have been omitted for clarity).

The value of N can include both the number of rainfall events, and the number of locations (e.g. rain gauges) used in the assessment. In the case of the RMSF, since logarithms are taken, the measure is only defined for non-zero values of observed or forecast values above an arbitrary threshold (e.g. 0.2 mm, 1.0 mm).

More generally, all statistics may be quoted either for the full range of rainfall events, or for rainfall above a threshold within the sampling period (e.g. >10 mm in a storm event). For flood forecasting applications, the focus should be on performance above the higher thresholds (e.g. 10 mm/hr) or during specific events which are known to have caused fluvial flooding.

The bias is intended to give an indication of systematic errors (e.g. consistent overestimation) whereas the RMS and RMSF errors should give an indication of the accuracy with respect to random error. However, when errors are random, the bias values can be deceptively small since large errors may tend to 'cancel out'. Also, both the bias and RMS are not normalised and so cannot easily be compared between locations, and will tend to be biased towards larger events.

Due to the equality Ln(a)-Ln(b) = Ln (a/b), the RMSF can also be interpreted as the average of the ratio between rain gauge and radar/Nimrod values, and has an ideal score of 1.0.

It is important to note that both the RMS and RMSF do not distinguish between over and under prediction, and are very sensitive to outliers, so that deceptively poor scores can be obtained due to only a few outlying values. The RMSF is also sensitive to ratios, rather than absolute values, so that errors in small amounts of rainfall can also have a large impact (unless only values above a threshold are used).

Table 6.1 illustrates this point for three hypothetical cases in which a similar RMSF score is obtained for three very different samples of ten events/point values.

Table 6.1. Illustration of the impact of outliers on RMSF scores

RMSF	Ratios (radar/Nimrod to rain gauges) for each of the ten events									
1.64	0.21	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.63	2.0	2.0	2.0	2.0	2.0	1.0	1.0	1.0	1.0	1.0
1.63	3.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

The other main type of performance statistic relates to the likelihood of rainfall above a threshold (e.g. 1 mm) being detected in a given interval (e.g. 1 hour) at a point (e.g. a rain gauge) and is based on a so-called contingency table (Table 6.2).

Table 6.2. Example of a Rainfall Detection Contingency Table

	Rain (radar/Nimrod)	No Rain (radar/Nimrod)
Rain (rain gauge)	A	B
No Rain (rain gauge)	C	D

so that the following measures of success can be defined:

- Probability of Detection (POD) = A / (A+B)
- Critical Success Index (CSI) = A / (A+B+C)
- False Alarm Rate (FAR) = C / (A+C)

These statistics relate simply to whether rainfall is detected above a given threshold, and not to the amount of rainfall above that threshold. Nevertheless, for assessing accuracy in flood forecasting applications, the totals above the larger threshold values (e.g. 10 mm in one hour) can be informative. Ideal scores are 1.0 for POD and CSI, and 0.0 for FAR.

6.2 Rainfall Actuals

6.2.1 Introduction

Within the Agency, the main techniques used for detecting actual rainfall are tipping bucket rain gauges, the Met Office's composite weather radar product as delivered through Nimrod, and site specific radar processing algorithms, such as those used in the Hyrad and WRIP software.

6.2.2 Tipping Bucket Rain Gauges

Errors in individual rain gauge measurements can arise due to the design of the instrument, the exposure to prevailing weather conditions, the height and situation in which the gauge has been installed, and the sampling time. In heavy rainfall, additional factors such as splashing (in or out), losses whilst the bucket is tipping (quantisation errors), and submergence (for pit installed instruments), may also have an effect.

Snowfall can also complicate interpretation of measurements by blocking or covering the gauge. For heated rain gauges, there will generally be a time lag between occurrence of snowfall and recording of a 'tip' and anomalous tips may arise from drifting snow entering the gauge.

Regarding the accuracy of rain gauge measurements, guidelines are often catchment and event specific, and may not always apply to other situations. However, when used for daily rainfall totals, it is generally thought that tipping bucket gauges can measure daily rainfall to within an accuracy of 0.6 to 1.6 mm (British Standards Institute, 1996). For sub-daily data, a rule of thumb (Reed, 1984) is that a 0.5 mm tipping bucket rain gauge reporting at half hourly intervals will define the average rainfall intensity in each half hour to within 1 mm/hr.

Regarding the spatial sampling accuracy, the Rainfall Collaboration Project study (Met Office, 2001b) showed that, for hourly accumulations, a 4 km mean spacing (i.e. 1 gauge per 16 km^2) would sample the 99% percentile of hourly catchment rainfall intensities to within 0.5 mm (the corresponding value for the 95% percentile was a 6 km spacing).

For daily totals, a single gauge in the 120 km^2 catchment was found to be sufficient to limit errors, on average to ±10%. In interpreting these results, it is worth noting that the catchment was generally low lying (elevations 35-195 m) and a denser spacing may be required where rainfall variations due to topography are more pronounced. More generally, the accuracy of catchment average rainfall estimates can depend on:

- The type of rainfall event(s) considered and/or season (convective, frontal, orographic etc)

- The location of the catchment(s) (Region, country etc)
- The elevation and topography of the catchment(s)
- Localised effects in the catchment(s) (coastal/inland, valley orientation etc)

Table 6.3 gives some other examples of findings within the UK regarding optimum rain gauge densities.

Table 6.3. Examples of findings for optimum rain gauge density for flood forecasting applications in the UK

Location	Region	Area (km^2)	Recommended gauge density
Soar	Midlands	1360	1 rain gauge per 150 – 180 km^2 was identified as optimum for average storm conditions in the Soar catchment (a Midlands catchment of 1360km^2 with an average rainfall pattern that is relatively spatially uniform) (Environment Agency, 1998c)
Dee	Wales	2137 (but results are for 60 sq.km subcatchments on average)	The number of rain gauges per 100 km^2 to resolve hourly rainfall to within 10 or 20 % was found to be approximately: - Extremely uniform rain – 1 gauge for 10% - Typical widespread rain – 3 gauges for 10% - Typical showers – 4 gauges for 20% - Extremely isolated showers – 6 gauges for 20% (Collier, from World Meteorological Organisation, 2000)
Brue	South West	120	1 gauge per 36 km^2 was sufficient to resolve the 95 percentile hourly storm rainfall to within 0.5mm (Met Office, 2001b).
Cardington		25	For 16 rain gauges, the RMS error for hourly accumulations at a single gauge versus the 5 km mean was about 0.35 (RMSF 2.2) over 188 events (Kitchen and Blackall, 1992)

The Kitchen and Blackall (1992) study is significant in that the Met Office use this as one of their benchmarks by which to judge radar rainfall accuracy. If using rain gauges alone, an RMSF score of 2.2 is achieved in comparisons of areal average values with a single rain gauge, then a similar score with weather radar/rain gauge comparisons indicates that radar is performing at least as well as a typical operational network of rain gauges.

6.2.3 Weather Radar

Weather radar measurements of areal rainfall can be affected by both permanent (physical) limitations in the weather radar network (locations/spacing of radars, topography etc), and by transient factors arising from meteorological phenomena (e.g. bright band effects, anomalous propagation etc).

To infer rainfall intensity at the ground from the reflected radar signal, it is necessary to apply correction factors which account (to some extent) for these effects. These factors can be large; for example sometimes reaching almost a factor of 10 for the bright band correction.

The Nimrod analyses (i.e. actuals) include corrections for most of these factors which have greatly improved the accuracy of the product. Recent Met Office performance figures suggest an RMSF of about 2.0 is now obtained for rainfall actuals under most conditions except at extreme range (Harrison *et al*, 2000).

Table 6.4. Source and impact of errors on radar rainfall estimates

Factor	Impact on raw radar estimates of rainfall	Type of event in which significant	Reason
Attenuation	Underestimation at long ranges	All	Reduction in energy reflected masking rainfall at longer ranges
Range	Underestimation of peak rainfall	All	At longer ranges, the resolution (grid length) increases reducing estimates for peak rainfall, and the attenuation/beam height also increases. Also, only a fraction of the rainfall is detected.
Beam elevation	Various	All	The lowest beam can be above low level precipitation (causing underestimation) or the highest beam may overshoot the top of rain bearing clouds (causing underestimation); the lowest beam may miss low level evaporation (causing overestimation) or precipitation growth (causing underestimation); and may miss translation of rainfall due to wind etc (causing variable effects)
Bright-band	Overestimation if encountered at short range; variable effects if at longer range	Typically within 75km of the radar in frontal/winter, 100-150km in summer conditions	The reflected signal increases without any corresponding increase in rainfall (the brightband typically lies about 1000m above the ground in winter frontal conditions but rises in warmer summer conditions). At long range, brightband and overshooting errors can sometimes compensate for each other.
Heavy rainfall	Underestimation	All	Most radar processing algorithms assume a single 'average' drop size distribution but drop sizes are larger in heavy rainfall
Hail	Underestimation	Thunderstorms	Increase in reflected energy compared to rainfall
Anaprop	Various	Cold outflow from thunderstorms	Anomalous echoes and decrease in range due to the beam meeting the ground
Occultation by topography	Underestimation	All	Radar 'sees' less of the rainfall system

To examine this performance in more detail, it is convenient to consider the two main sources of errors in radar data separately:

- Physical limitations (range, minimum beam elevation, topographic effects)
- Meteorological factors (bright band, low level growth, anaprop etc)

Physical limitations

The main physical limitations on radar performance arise from the beam elevations used (affecting the heights at which precipitation/cloud can be detected) and the fact that the beam width also increases with distance from the radar (affecting the probability of detecting precipitation, particularly light rain and drizzle, and degrading the spatial resolution). Ground clutter arising from hills, buildings etc may also affect the accuracy of measurements and block the path of the radar beam(s).

The Met Office has recently developed a radar coverage quality index derived from the Probability of Detection of precipitation based on an analysis of rain gauge and radar data for the period June 2000 to July 2001. This index identifies seven categories of detection probability, based on distance from the radar, beam elevation/height, and ground clutter encountered by the beam, as shown in Table 6.5. Whilst the PoD does not explicitly provide a measure of radar rainfall estimation accuracy at any given location, it can be used (with caution) as an indicator of likely radar data quality – however there is presently insufficient information available to draw any general conclusions relating the accuracy of other statistical measures to the quality class .

Table 6.5. Radar coverage quality index scheme (after Harrison and Gould, 2001)

Range (km)	Data resolution (km)	Quality Class	POD (%)	Basis for classifier	Comments
0-50	1	1 (1A)	94	Beam < 500 m	Highest quality data. Detection rate of close to 100% for all types of rainfall
0-50	1	2 (1B)	91	Beam > 500 m	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 < 1000 m	
50-100	2	5 (2B)	86	Beam > 1000 m	
100-250	5	6 (3A)	82	Beam < 2000 m	
100-250	5	7 (3B)	73	Beam > 2000 m	Lowest quality data, only deep precipitation will be detected

Table 6.6 shows a breakdown of the percentage of the Agency regions falling into each of the coverage classes. The North-East and North-West are the only regions with radar coverage in the lowest coverage quality class (with 26.6% and 21.7% respectively). When extended to include the second poorest coverage level, the figure for the North-East increases to 41.5%. The other regions with poor levels of coverage are Anglian (26.3%). Southern (23.4%) and Wales (11.8%). For England and Wales combined, the analysis suggested that approximately 34% of the landmass falls within 50 km of a radar site (and will therefore benefit from 1 km resolution data when the higher resolution radar data products become available). In contrast, over 16% of England and Wales is at least 100 km from a radar for which only lower spatial resolution (5 km) data are available. Further detail on this analysis is presented in Met Office (2001b).

Table 6.6. Indicative radar coverage quality on a regional basis (% of region)

	'Good' (POD>90%)			'Medium' (83%<POD<90%)		Poor' (POD<82%)	
	1A	1B	1C	2A	2B	3A	3B
Anglian	15.0	4.7	4.4	45.8	3.9	26.3	0.0
Midlands	10.0	17.9	12.2	53.2	6.7	0.0	0.0
North-East	3.4	9.0	0.5	32.6	12.9	14.9	26.6
North-West	14.1	21.5	4.5	11.2	26.2	0.8	21.7
Southern	0.0	0.0	0.0	71.2	5.4	23.4	0.0
South-West	43.4	9.5	5.6	33.3	8.2	0.0	0.0
Thames	38.4	8.1	6.0	34.4	13.2	0.0	0.0

Wales	18.2	13.9	5.8	34.7	15.6	11.8	0.0

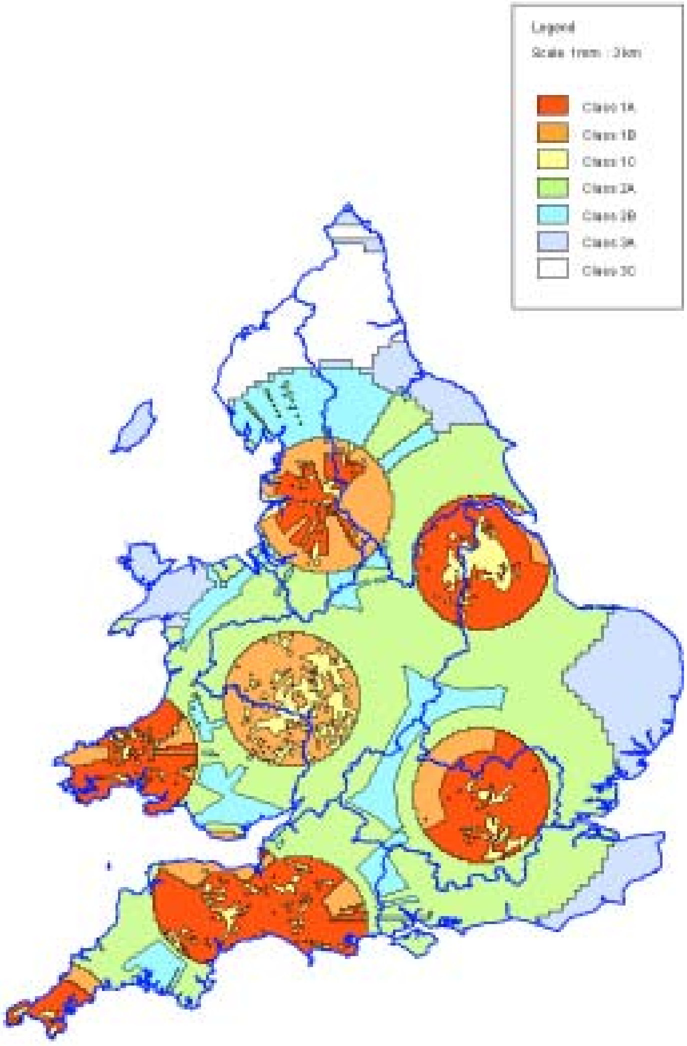


Figure 6.2. Indicative radar network coverage quality map (Source: Met Office, 2001b)

Meteorological factors

When considering performance during specific events, the main factors to consider are:

- The interval over which measurements are accumulated (e.g. hourly)
- The area over which the measurements are averaged
- The distance from the nearest radar
- The adjustment techniques which are used (rain gauge, vertical profile of reflectivity etc)

Figure 6.3 gives an early indication of the potential accuracy of weather radar data compared with rain gauge data, based on the findings of the Dee Weather Radar Project (CWPU, 1977).

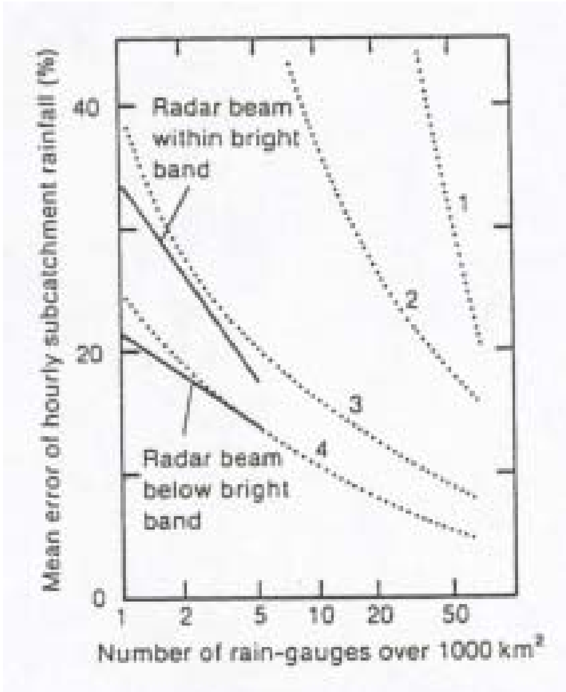


Figure 6.3. Differences between estimates of hourly sub catchment rainfall related to rain gauge density ***(1=isolated shower, 2=typical showers, 3=typical widespread rain, 4=extremely uniform rainfall) (World Meteorological Organisation, 2000)***

This project, which completed in the 1970s, suggested that, under carefully controlled conditions, and within 75 km of the radar site, using one rain gauge for adjustment, an error of the order of +/-20% could be achieved for hourly rainfall accumulations over areas of about 100 km^2, increasing to +/-40% when the radar beam intersects the bright band. The present operational network is believed to achieve similar levels of accuracy.

More recently, Golding (2000) reports that the Probability of Detection (POD) by Nimrod as a function of range is as follows:

For drizzle and light rain (<2mmh^{-1})	-	70% at 60 km range 20% at 200 km range
For moderate and heavy rain (>2mmh^{-1})	-	98% at 60 km range 95% at 100 km range 50% at 200 km range

These are average results so it is also instructive to examine the performance obtained in several of the largest flood events in recent years: Easter 1998, October 1998 and October 2000 (Table 6.7).

These results suggest that, during heavy rainfall events, over six hour or longer periods, Nimrod catchment total rainfall accumulations can approach, and in some cases, improve upon, estimates from rain gauge networks, particularly during widespread frontal events. As might be expected, performance decreases for localised events (as in 11-12 October 2000), but can still be more accurate than the rain gauge estimates.

The Met Office's long term goal for precipitation observations is to achieve a Root Mean Square log Factor (RMSF) of 1.25 at a spatial resolution of 0.5 km and a temporal resolution of 1 minute. This compares to a current performance level of 2.0. The RMSF is defined as the anti-log of the RMS log error (see Section 6.1.3) and typically uses hourly rain gauge data above a threshold as 'ground truth', and is essentially the average ratio between radar and 'observed' values for rainfall at one or more locations; for example, a value of 1.25 equates to an error of about ±10%. This requirement is based upon the perceived needs for distributed modelling of the precipitation run-off into rapidly responding urban drainage systems (Golding, 2000) although may exceed the limit of what can realistically be measured with present technology. Currently, the level of performance achieved is that for hourly accumulations the RMS log difference between a point measurement (rain gauge) and a 5 km x 5 km mean radar estimate is about 0.35 (RMSF=2.2) (Kitchen and Blackall, 1992; Harrison *et al*, 2001).

Table 6.7. Summary of Met Office analyses of Nimrod analyses during recent major fluvial flood events

Date	Description of Nimrod analysis
Easter 1998 (Harrison *et al,* 1999)	During this event, a band of convective storm cells producing the highest rainfall accumulations over the Midlands and Welsh borders on 9th April was within the area of coverage of three radars: Clee Hill, Chenies and Ingham. For daily accumulations, there was reasonable agreement over the Midlands and Welsh Borders but the radar derived totals underestimated rainfall around Peterborough to the east. For the two rain gauge locations recording the highest rainfall (Pershore and Church Lawford), daily totals were within a few percent of rain gauge values.
22-24 October 1998 (Harrison 1999)	Between 22nd and 24th October 1998, several bands of heavy rainfall and showers crossed Wales. Three-day totals exceeded 100 mm in upland areas and serious flooding resulted, particularly in the South Wales Valleys. Orographic enhancement was significant. In situations where strong moist low level winds produce hill fog, rain falling through the fog, low level enahancement of rainfall may dramatically increases the rainfall at the surface. This process of orographic rainfall enhancement typically occurs in the lowest 1.5 km of the atmosphere and may be undetected in South Wales and other upland areas of the UK. However, estimates of low level enhancement are included within the Nimrod system and added onto the component of rainfall detected by the radar. For rain gauges recording above 50 mm, storm totals were typically within 10 mm of the rain gauge totals within 150km of the Clee Hill radar.
9-12 October 2000 (Environment Agency, 2001b)	Severe flooding was reported in south east England associated with a persistent heavy band of rainfall orientated SW-NE, occurring after storms on the previous two days. This was associated with a trough wrapped around an area of low pressure centred over northern England. Radar images showed that the most intense rainfall was in the valleys to the northeast of Brighton including the towns of Uckfield and Lewes, where serious flooding occurred. Storm totals of more than 50mm were measured by radar (at a 5km resolution), with Met Office rain gauges recording a maximum of about 30 mm, and non Met Office gauge measurements typically exceeded 80 mm. The Nimrod forecasts generally showed reasonable agreement with observed values, predicting some 60% of the actual 6 hour rainfall which was estimated to occur in the Lewes/Uckfield area.
29-30 October 2000 (Environment Agency, 2001b)	This event caused widespread flooding in many parts of the UK and was initially associated with a deep low NW of Scotland. Over an 18 hour period starting at 1600 on the 29th, widespread rain over Wales moved eastwards and expanded in area to cover most of southern Ireland and the UK as far north as north Wales and the Wash by midnight. This then moved northwards to the Humber and a clear slot developed southwest of Wales separating the rain band into two parts covering southern and northern England before clearing eastwards by 1100 on the 29th. The radar images show that rainfall was in the range 16-32 mm per 6 hour period across much of the country over the event, with regions in the range 32-64 mm in the southwest and Manchester area. The analyses showed that for six hour accumulations radar estimates of rainfall were typically in the range 78-92% of rain gauge values over a 15 hour period. A detailed analysis of daily rainfall data during the event showed that daily accumulations were mainly in the range 32-64mm in western areas, and exceeded 64mm in places. Nimrod estimates were typically within 16mm of these rain gauge values.

6.3 Rainfall Forecasts

6.3.1 Short Term Forecasts (0-6 hours)

For short term forecasting, the two main products available are Nimrod and the radar-only methods incorporated into the HYRAD and WRIP systems.

Table 6.8 indicates the current performance level achieved by the Nimrod and mesoscale model systems of the Met Office, using the RMSF computed from 15 km x 15 km averages and verified against quality controlled radar actuals. As might be expected, for lead times of up to about 2 hours, Nimrod provides significant improvements over estimates from the mesoscale (NWP) model, but the estimates converge as more use is made in Nimrod of the model output at longer lead times.

Table 6.8. QPF Performance for 0-6 Hour Forecast Lead-Time in the period Sept 1998-August 1999 (partly adapted from Golding, 2000)

Lead time (h)	1	2	3	4	5	6
	Forecast Root Mean Square Log factor (RMSF)					
Nimrod	2.4	3.7	4.2	4.3	4.4	4.4
Mesoscale model	4.1	4.2	4.3	4.35	4.4	4.4

However, studies in Thames region have suggested that Hyrad advection forecasts can represent average conditions better than Nimrod for lead times up to about 1.5 hours ahead, with Nimrod performing better for longer lead times and for exceptional events (Environment Agency, 1998c).

A recent Met Office study (Driscoll *et al,* 2000) has also examined the performance of Nimrod in generating heavy rainfall alerts meeting the National Severe Weather Warning Service criterion of rainfall exceeding 15 mm over a three hour period. Nimrod output was evaluated for four test locations in the South-West, North-East and Thames regions and southern Scotland over the period 27 May to 30 Sep 1999. The Probability of Detection was estimated to be about 91% for actuals, 60% for 0-3 hours ahead, and 32% for 3-6 hours ahead. However, it was noted that the trial period was in summer/autumn and so may not apply to the frontal conditions more typical of other seasons.

These results, and other studies (e.g. Environment Agency, 2001b), suggest that the main characteristics of the current Nimrod forecasting product are:

- Rainfall areal estimates are broadly unbiased
- Rainfall peaks are detected best for small grid intervals (e.g. 1 km)
- For rainfall peaks, a bias can arise at lead times from 3-6 hours as these forecasts are dominated by the lower resolution of the mesoscale model (12 km), especially during convective events of subgrid scales
- Anaprop effects are less significant at longer lead times due to the dominance of the mesoscale model as opposed to pure advection
- The Probability of Detection of rainfall is significantly higher for frontal events than convective events
- The Nimrod algorithms are optimised for frontal events and generally perform better in these circumstances
- Forecast accuracy can vary according to the timing of the most recent mesoscale model run (i.e. on a 6 hour cycle with an additional 3 hours for data assimilation before the run)

Regarding the forecasting of convective events, problems noted with the Gandolf methodology (now incorporated into Nimrod) include:

- The system can have problems developing convection in new areas of ‘clear air’
- Forecasts can tend to ‘pulse’ according to the diurnal cycle

- The system has problems decaying the rainfall from severe (mature) storms
- The technique works best in conditions of high wind shear (changes in direction with height) rather than when storms are triggered by other factors (e.g. sea breeze convergence, heating from hills)

Table 6.9 summarises the observations from this section regarding the accuracy of Nimrod and radar-only forecasting techniques. It is emphasised that these results are often based on specific events/short periods/specific locations, and that future joint Agency/Met Office work should lead to a better understanding in the near future.

Table 6.9. Indicative summary of Nimrod accuracy estimates for hourly and other accumulations over areas of 100-200 sq. km or more in heavy rainfall

Range/lead time	0-50km			50-100km			100-250km		
	POD	RMSF	% error	POD	RMSF	% error	POD	RMSF	% error
Actuals	94-98	1.7-2.3	10-20	94-98	2.0-2.3	20	50-94	2.3-2.6	20-40
1		2.4	Similar		2.4	Similar			
2		3.7			3.7				
3		4.2			4.2				
4		4.3			4.3				
5		4.4			4.4				
6		4.4			4.4				
0-3	60			60					
3-6	32			32					
0-6			10-30						
Storm total			20						

6.3.2 Longer Term Forecasts (Beyond 6 hours)

Regarding accuracy of Heavy Rainfall Warnings and Daily Weather Forecasts, it is important to remember that the forecasts are based largely on the output from the Met Office and other NWP and ensemble models, and at longer lead times rely heavily on the global model. Even for the relatively high resolution mesoscale model, the minimum grid length is about 12 km, and the model can only realistically represent rainfall features extending to at least four grid lengths except where there is very strong forcing from the surface (Golding, 2000). This feature of the model therefore places a minimum resolution of about 50 km on any forecasts beyond 3-6 hours ahead; equivalent to an area of 2,500 km^2. This should be considered when interpreting rainfall forecasts for these lead times.

Another factor to consider is that the models only produce hourly forecasts at six or twelve hourly intervals, with up to a three hour delay before the forecasting run whilst data are assimilated. This means that the accuracy of forecasts can vary depending on when the forecast is issued relative to the timing of runs of the model.

The accuracy of long term forecasts has recently been reviewed as part of a joint Agency/Met Office study (Environment Agency, 2001b). The study reviewed the quality of rainfall forecasts nationally for Oct-Nov 2000; in particular for the period 27 Oct to 7 Nov. An additional period, 12-19 Oct 2000 was considered for Southern Region only. The study considered the accuracy of Heavy Rainfall Warnings and Daily Rainfall Forecasts and also looked at the performance of the mesoscale model and Nimrod forecasts in relation to specific areas. The key findings of this study are presented in Section 7.2.2c and summarised in the following two paragraphs.

For Daily Rainfall Forecasts, these analyses suggested that, for the days with heavy (flood generating) rainfall, there were problems with persistent over or under-estimation in some regions, with the heaviest falls almost all underestimated. Forecast accuracy was also found to vary in time; most commonly with 2-3 day ahead forecasts of heavy rainfall being reduced from 24-36 hours ahead, then increased again from 6-18 hours ahead.

Similarly, the main finding regarding the accuracy of Heavy Rainfall Warnings was that forecast accuracy was found to vary significantly both over the forecast period and with forecast lead-time. There was some evidence that for up to 12 hours ahead, forecast skill scores could be surprisingly low, with better results observed for lead-times of 12-18 hours. This may in part be due to the timing of model runs, although Golding (2000) mentions the so-called 'spin-out' effect, where precipitation is deficient in the first few hours of NWP model runs as the effect of the choice of initial conditions decays.

7. FLOOD FORECASTING NEEDS FOR RAINFALL MEASUREMENTS AND FORECASTS

7.1 Introduction

This chapter reviews how rainfall measurements and forecasts are currently used within the Agency for flood warning and forecasting, and discusses some possible future requirements in terms of accuracy, speed of delivery and other considerations.

The discussion begins with an analysis of current Agency practice and some of the operational problems which have been encountered. This review work is based on discussions with Agency staff, published reports, and the consultant's experience with a number of operational systems. In particular, it draws upon the findings of three recent R&D projects which included consultation exercises to identify Agency requirements for a range of issues, including rainfall measurements and forecasts for use in flood warning and forecasting. These projects were:

- Rainfall Collaboration Project, Environment Agency/Met Office (Met Office, 2001b)
- National Flood Forecasting Modelling Systems Strategy Preliminary Study (Environment Agency, 2001c)
- Flood Forecasting and Warning Good Practice Baseline Review (Environment Agency, 2000b)
- Consultation undertaken during this project

For convenience, these findings (as they relate to rainfall measurement and forecasting) are reproduced in Appendix D. Topics discussed in the present chapter include the use within the Agency of weather radar data, and experience with using recently developed forecasting systems such as Nimrod and Gandolf.

One of the outcomes of this review work is an indication of areas in which improvements could be made in the rainfall data and forecast products that are currently available. Section 7.3 considers this important question in more detail, from the point of view of the data and products that - in an ideal world - would be available to the Agency's flood warning staff, and the corresponding accuracy etc.

7.2 Agency experience of rainfall measurements and forecasts

7.2.1 Current use of rainfall measurements and forecasts

Weather radar data and forecasts

The recent National Weather Radar Strategy study (Environment Agency, 2000a) provides an excellent review of the current usage of weather radar data and forecasts within the Agency, and this has been supplemented here by the information given in Appendix D and discussions during this project.

As of mid-2000, there were four stand-alone systems in use for the processing and display of weather radar data:

- Hyrad - developed by CEH, Wallingford (and including radar-only based rainfall forecast techniques) (North-East, Anglian, Southern)
- MicroRadar – developed by Weather Services International (Thames, Wales, Midlands)
- STORM – developed by the University of Salford (South-West region)
- MIST – developed by the Met Office (South-West, Thames, North-East)

From 2002 all regions have also had access to the National Interim Weather Radar Display System (NIWRDS) which will supercede Hyrad (on which it is based), Microradar, and STORM. NIWRDS will provide full access to the Met Office's Nimrod products, the facility to overlay GIS coverages on the images (e.g. rivers networks, catchment boundaries, coastlines etc), radar image archiving and replay facilities, and the option to calculate catchment average rainfalls. The system is Windows based and is implemented as a harmonised Agency desktop application, making it available (subject to licencing) over the Agency's Wide Area Network on the standard desktop. NIWRDS provides a nationally consistent platform for the display of radar data products, and is fully compatible with the National Flood Forecasting Modelling System (NFFMS) Specification currently being developed by the National Flood Warning Centre.

Four further integrated data management and forecasting systems have the facility to display and use weather radar data:

- WRIP – developed initially by University of Salford, and now being further developed by the University of Bristol (South-West, North-West)
- REMUS – developed by Weather Services International (Midlands)
- NTS Radar Picture System – developed by Serck Control Systems (North-West, North-East)
- CASCADE – developed by Thames region and incorporating prototype HYRAD routines (Thames)

These systems commonly locate rainfall areas from radar (usually Nimrod) data and are capable of generating rainfall accumulations at the catchment scale. Some use single-site radar data, whilst others use fully adjusted Nimrod products (the network composite).

A GIS system for processing and displaying radar data called EnviroMet® developed by the Met Office is currently being trialled in the North-West region. An advantage of EnviroMet® is that catchments can be easily defined by the user, making accumulation estimates more flexible and adaptable to operator needs. There is also the possibility of integrating the new Met Office MOSES data product. This could provide a forecast, not only of rainfall over a specified area, but also effective rainfall, SMD or an estimate of run-off.

The National Weather Radar Strategy concluded that, at present, in most regions radar data and radar-based forecast products are used mainly in a qualitative sense (tracking storms etc) and are not used operationally in flood forecasting models (summary findings presented in Table 7.1).

Table 7.1. Agency use of Nimrod actuals and forecasts for flood warning and forecasting as of mid-2000

(Source: National Weather Radar Strategy and present project)

Region	Use in forecasting
Anglian	Radar data and radar-based forecasts are currently used only qualitatively. Plans are in place to use radar data more quantitatively in forecasting models for those catchments with good coverage. It is only intended to move to radar in preference to rain gauges after off-line assessment
Midlands	Observed radar data (single site) are delivered as catchment rainfall totals but are not used operationally in rainfall runoff modelling due to low confidence in the quality of the data. However Nimrod forecasts are routinely incorporated into model forecasts.
North East	15-minute radar rainfall accumulations are generated (observed and forecast) for selected catchments based on locally calibrated raw single site data. There is the option to feed these data into Real Time Models but this is not enabled at present. Rain gauge data and Met Office synoptic predictions of rainfall are preferred. Longer-term forecasts are also used: for up to 36 hours ahead the six 6-hour rainfall depths are disaggregated into 15 minute totals and can be manually fed into rainfall runoff models.
North West	15-minute radar composite data is fed into rainfall runoff models running on the Regional flood forecasting system, which calculates rainfall accumulations from observed and forecast radar fields.
Southern	Radar data not currently used quantitatively due to perceived poor coverage and data quality. No on-line system is currently available to input data into forecasting models
South West	The regional flood forecasting system uses Nimrod actuals to derive catchment rainfall totals for 100 potential rainfall runoff forecasting sites. These totals can be displayed and fed into forecasting models. At present, models are calibrated using rain gauge data due to "unreliability of radar data". Nimrod forecasts are also routinely used as input into rainfall runoff forecasting models.
Thames	Radar actuals and forecasts from a number of sources are available for use in real time flow forecasting models. Subcatchment totals are generated from the appropriate 2/5 km datasets. Single site and Nimrod subcatchment data are routinely fed into rainfall runoff models.
Wales	No quantitative use of rainfall forecasts although radar images are used to assist with rainfall and flow forecasting.

General use of rainfall data and forecasts

Another view of the use of rainfall data and forecasts within the Agency is to consider the operational applications for flood warning and forecasting (e.g. determining Duty Rosters) and Table 7.2 presents an assessment of current practice as identified in the recent "Flood Forecasting and Warning Good Practice Baseline Review" study (Environment Agency, 2000b). It must be emphasised that only a few examples of good practice are presented, and other regions may also use some of these techniques in their operational work. Also, some of the findings of the study have been overtaken by recent developments.

Table 7.2. Examples of good practice in use of telemetered rainfall data/forecasts for flood warning/forecasts (Source: Flood Forecasting and Warning Good Practice Baseline Review, Environment Agency, 2000b)

Application of rainfall data/forecasts	Examples of good practice within Agency regions
Regions require the provision of weather services to allow them to produce an accurate and timely flood forecasting and warning service	This matter has been addressed by the "Weather Services Review" (Environment Agency, 1999). All regions implemented new arrangements for a single Agency/Met Office agreement for provision of weather service by September 2000
Warning of extreme weather and short term updates	Amended from source document: <u>All regions</u> should receive Severe Weather Warnings, and Heavy Rainfall Warnings.
Quantitative use of radar data in forecasting models	Midlands and Thames regions have this facility. In Midlands, Nimrod forecasts up to six hours ahead are fed into the 'Flood Forecasting System'. In Thames, single site and Nimrod sub-catchment data are used in rainfall runoff models within the RFFS. North-West, North-East and South-West use data for small scale quantitative forecasts. Quality of existing data has been recognised by NWRS and the existing R&D programme as needing improvement
Receipt and display of weather radar information at region and area offices	Thames, Midlands and North-West regions have weather radar information displayed at regional and all area offices
Detecting and tracking of thunderstorms	GANDOLF is currently being evaluated by Thames Region but it is accepted that the system needs further development
Need to incorporate data on antecedent conditions into monitoring/forecasting	South West region use catchment wetness index and antecedent precipitation index based on MORECS data received from the Met Office, for fluvial monitoring
Accurate and reliable network of short-period rain gauges providing coverage of the region	In accordance with the Easter Floods Action Plan all regions are reviewing gauge coverage (see also, Met Office, 2001b).
Provision for recording snow fall and monitoring its contribution to runoff	Midlands Region have heated rain gauges to monitor amounts of snow fall and a network of snow observers who investigate and report on snow density etc. Snowmelt models are used by Anglian, North-East and Midlands Regions. The North-East region has experience of snow pillows (Refer to Section 2.4)
Regional telemetry systems to provide accurate and timely data for use in facilitating effective flood warnings	North-West and North-East have recently commissioned the Agency's most up to date and effective telemetry system (NTS). Anglian has initiated the replacement of their old system. Midlands, Wales and Thames are jointly procuring new telemetry systems under the Joint Telemetry Project (JTP).
Clear and easily assimilated display of current situation and trends of rainfall at regional and area offices	The new North-West and North-East regional telemetry systems and the planned systems for Anglian and South-West, and Midlands, Wales and Thames will all have this functionality..

7.2.2 Review of operational problems and issues

<u>Problems highlighted in previous studies</u>

a) *The Bye report, 1998*

When considering current operational problems and issues regarding the use of rainfall data and forecasts, the Met Office's recommendations in the Bye report provide a useful starting point. The Bye report (Environment Agency, 1998b) was commissioned following the Easter floods of 1998 and reviewed flood warning and forecasting practice in the UK. Concerning meteorological requirements, a model (i.e. ideal) weather information service was proposed, together with a better common understanding (Met Office/Agency) of the prevailing weather systems. It was noted that, in some other countries (e.g. the USA, Australia), the flood forecasting and warning service is fully integrated with the meteorological service and benefits from direct consultations and shared data sources. Also, it was noted that in the UK not every Agency region is able to access the rainfall data collected by neighbouring region's telemetry systems, which limits understanding of rainfall on or near to catchments at the boundary of each region. The Met Office's submission included the specific proposals given in Table 7.3.

Table 7.3. Summary of Bye report recommendations for improving rainfall forecasting practice

Item	Interval	Description
Nimrod	5 minute	Dissemination to all Agency Regions of quality controlled 2 km/5 minute single site data, UK composite, Regional Radar composite (5 km/15 minute and 2 km/5 minute if required) and rainfall forecasts from the Met Office Nimrod system through high speed resilient telemetry links
Routine contact with Civil Centres	Daily	Routine daily conference between Agency Flood Warning Duty Officers and Met Office Civil Centre Forecasters. Routine daily update of probability of rainfall accumulations by fax, telex or electronically exceeding relevant thresholds. Inclusion of Agency Flood Warnings in national and regional TV and broadcasts
Daily Rainfall Forecasts	Daily	Detailed daily forecasts for the next 48 hours to each Region by fax, telex or email/intranet sub divided to cover hydrological zones. Forecasts of maximum rainfall totals expected in each hydrological zone within each Region for 6 hour intervals with confidence levels. An indication of the general synoptic weather situation for the period, with a detailed summary for each day to include other meteorological elements.
5-day ahead forecasts	3 times weekly	Three times weekly (Mondays, Wednesdays and Fridays) 5 day ahead forecast as outlined above but for 12/24 hours rainfall forecast periods and rainfall accumulations with an outlook for weather trend for days 6 to 10
Back up consultancy service	As required	A 24 hours, 365 days per year back up consultancy service to enable Agency's staff to clarify warnings, routine forecasts and discuss short term weather prospects.
Synoptic conditions to 5 days ahead	12 hourly	Twice daily North Atlantic actual and forecast pressure and frontal fields charts for each day out to 5 days ahead
Senior management meetings	Annual	Annual meetings at national senior management level to discuss strategic issues and at middle management level to review regional services and present verification reports. Non operational contact person within each Agency Region to coordinate services across all functions and be the trouble shooter. Visits by Met Office Civil Centre forecasters and Flood Warning Duty Officers to each others Operations centres. Radar Data Quality Management Group Meetings
MOSES (successor to MORECS)	Hourly	5 km x 5 km areal estimates of soil moisture deficit, actual and potential evaporation etc to help assess catchment states and runoff
Severe Weather Warnings	As required	Warnings up to 5 days in advance of extreme events likely to cause widespread disruption to human activity provided as part of the public Met Service
Provision of information during potential flood events	As required	Warnings to Agency Flood Warning Duty Officers by fax, telex, or electronically with back-up telephone call to confirm receipt. Flexible warning criteria for different hydrological and catchment characteristics to include best estimates of rainfall quantities and intensities above the relevant warning criteria, along with the likely times of occurrence. Probability of rainfall intensities and amounts in different 'bands'

b) National Weather Radar Strategy, 2000

The National Weather Radar Strategy (Environment Agency, 2000a) also provides a useful summary of some of the current problems which Agency staff has identified in current procedures for disseminating and using rainfall data and forecasts (Table 7.4). Some of these points are expanded upon in the remainder of this section. A series of recommendations flowed from this analysis of shortcoming and these are shown in Table 7.5.

c) Joint Agency/Met Office Report into Performance of Rainfall Forecasts, 2001

A joint Environment Agency/Met Office study (Environment Agency, 2001b) investigating the operational performance of rainfall forecasts received by the Agency was completed in October 2001. The study reviewed the quality of rainfall forecasts nationally for October-November 2000; in particular for the period 27th October to 7th November nationally. An additional period, 12th-19th October 2000 was considered for Southern Region only. The study considered the accuracy of QPF in Heavy Rainfall Warnings and Daily Rainfall Forecasts and also looked at the performance of the mesoscale model and Nimrod forecasts in relation to specific areas.

An attempt has been made to numerically compare the QPFs in Daily Rainfall Forecasts and Heavy Rainfall Warnings, with actual recorded values – using approaches that varied from region to region. For example, in some regions the forecasts were compared to rainfall measurements from, say, five rain gauges, located over the forecast area; whilst in other regions an area average was estimated from as many as 50 rain gauges. In either case, a simple skill score system was adopted, based on percentage range between actual and forecast. For Heavy Rainfall Warnings forecast delivery time and time of receipt was also assessed and included as part of the score. The analysis took place for event data covering a short-period of time, and, as such the results are biased to specific events.

Table 7.4. Shortcomings in the current situation (National Weather Radar Strategy, 2000)

General area	Problem
Communications	Problems with the communications network in some regions can result in occasional loss undermining user confidence
	The communication network restricts the dissemination of radar products resulting in the best available data not being used operationally e.g. quality controlled single site data
	Slow line speeds result in unnecessary delays in the receipt of radar products, in some instances this can be as high as 20 minutes, and inother data transmissions can be overwritten or lost altogether
Data processing systems	The relatively large number of systems in use across the regions is considered to be detrimental to the development of an integrated approach to flood detection and forecasting across the Agency
	The development and maintenance of a range of systems is both inefficient and uneconomical and results in duplication of effort
	There is a continuing requirement to use radar data operationally in two ways; for qualitative use via display systems and for quantitative use linked to forecasting and telemetry systems. These two requirements are often addressed independently of each other and a more integrated approach is required in future
Coverage	Radar coverage is poor in certain areas, for example South Wales, North Wales, southern England (Kent), Northumbria and parts of the Midlands and East Anglia (Easter Floods 1998 area)
	Radar coverage can be deficient over significant urban areas such as the East Midlands connurbations and the Welsh valleys. Poor coverage over these and other areas limits the Agency's ability to deliver a comprehensive and targeted Flood Watch and Flood Warning Service
Quality	Poor confidence in the quality of radar data restricts the quantitative use of this information in flood forecasting
	Occultation (screening) can be a problem in certain key areas where the radar beam becomes blocked over sensitive river catchments e.g. Clee Hill and the Welsh mountains. This leads to significant under estimation of rainfall accumulations
	Radar performance can be poor in mountainous areas (e.g. in Wales) and orographic enhancement is often not picked up by the radar network again resulting in rainfall accumulations being significantly underestimated
	A number of radars are known to perform poorly at long range, notably Ingham and Clee Hill
	Radar data quality can suffer due to the effects of bright band (especially during the winter months), anaprop and hail contamination (especially in convective situations). This can result in significant over estimation in rainfall accumulations
Flood warning service delivery	Improved accuracy, reliability and coverage are required to facilitate the delivery of the new four staged warning service
	More accurate and reliable rainfall forecasting products are required to help deliver the Flood Watch service, including better forecasting of summer storms over urban areas
	There is a need to generate subcatchment rainfall accumulations over additional areas as the extent of the flood warning service increases
	Improved data archiving services are required to facilitate modelling work and post event analysis
	A comprehensive training programme is required to support new staff. This should focus on developing interpretation skills relating in particular to data quality

Table 7.5. Recommendations for improvements in rainfall forecasting practice (Adapted from: National Weather Radar Strategy, 2000)

Topic	Description
Communications and Hardware	Radar data and related products will be disseminated from the Met Office to the Agency by file transfer over a limited number of high speed and robust communication links
	Each region will put in place the appropriate communication infrastructure to capture all relevant radar based products for onward transmission to regional display and forecasting systems. Data will be accessible from each Regional Forecasting Centre, Area Incident Room, and the relevant duty officer's home
	All communication systems and related hardware and software will have the appropriate level of resilience and 24-hour support to ensure operational availability of this business critical service
Radar display systems	The Agency will converge to a single national radar display system and each region will migrate to this system over a period of time. A user requirement and technical specification to be drafted and agreed by April 2001 with the aim of procuring a national display by June 2002
	In the interim, regions will be required to work with existing systems with any proposals for developing or modifying those systems to be agreed by and coordinated through the National Flood Warning Centre and National Weather Radar group
Links to models	Each regional forecasting centre will develop the capability of routinely feeding radar data and radar based forecasting products into real time flood forecasting models. The facilities needed to progress this work will be defined in conjunction with the National Flood Warning Centre and will conform to a national strategy when this is in place
Radar network	The Met Office and the Agency will complete an assessment of the future coverage of the radar network by April 2002. Any extension to or modification of the network will be accompanied by a robust business case and benefit assessment and will include a national submission to MAFF/NAW for grant aid on new capital equipment. It is recommended that any additional radar sites be commissioned by April 2008
	The Agency will adopted an integrated approach to the use of hydrometeorological information, including that from weather radar and rain gauge networks
Archiving data	Each regional forecasting centre will develop a local, selective archive for the storing of event based data, to include radar products and telemetry data. In future, each centre will also be able to access a long term radar archive being developed by the Met Office in Bracknell
Product delivery reliability and quality	Through the analysis of routine statistics and event based case studies, the Met Office and the Agency will strive to improve the reliability of delivery and quality of radar based products to help meet the levels of service required for flood forecasting and warning in England and Wales (resilience of delivery systems)

The main findings regarding Heavy Rainfall Warnings were:

- Forecast accuracy was found to vary significantly both over the forecast period and with forecast lead-time. There was some evidence that for up to 12 hours ahead, forecast skill scores could be surprisingly low, with better results observed for lead-times of 12-18 hours. The project team believe that this may be due to timing of global/local area NWP model runs, although Golding (2000) mentions the so-called ‘spin-out’ effect, where precipitation is deficient in the first few hours of NWP model runs.
- The spatial resolution is insufficient at present for real-time (quantitative) operational flood forecasting (but useful qualitatively)
- Rainfall alarm triggers are (in many cases) ‘legacy values’, defined over a number of years and now being applied in ways not originally envisaged.
- There can be significant variation in the detail of rainfall forecasts according to the experience and local knowledge of the Met Office Duty Officer and the strength of the relationship between the Agency Region and the Forecasting Officer.
- The manual dissemination of heavy rainfall and severe weather warnings (by fax with phone follow up) is a failsafe procedure. Any move to a more automated dissemination system will need to replicate this robustness.
- There are inconsistencies in the production/dissemination of Heavy Rainfall Warnings. For example, in North Wales the Dee District receives forecasts from Met Office Manchester, whilst the Gwynedd District get forecasts from Met Office Cardiff.

The main findings arising from a detailed analysis of 5 km Nimrod data (for October 12th, October 27th, November 6th 2001) were:

- ‘Nowcasts’ failed to identify the highest rainfall intensities. The project team note that this will arise by default from spatial averaging over 5 km grid cells, and that this aspect of performance may improve when higher spatial resolution data are used - the down-side being that increased spatial resolution brings with it an increased risk of placing rainfall in the wrong pixel.
- Nimrod forecast performance does not exhibit a continuous transition with increasing forecast lead-time; in fact, there is evidence to suggest an abrupt change in forecast performance at about 3 hours. The project team suggest that this might be a manifestation of the change-over from a linear (‘radar-only’) advection algorithm to NWP model output.
- Nimrod is an automatic system and the Met Office cannot verify in real-time the data produced

In conclusion a number of needs were identified:

- Further meteorological R&D is needed to improve rainfall forecasting and the quality of forecast products available (although it is recognised that much is already underway) especially on spatial resolution; timeliness and accuracy; Nimrod and NWP products; and the radar network.
- The Agency needs to be clearer on its requirements for rainfall forecast products, e.g. what accuracy, spatial resolution and lead-time is required for its applications (see below).
- The format of Heavy Rainfall Warnings and Daily Rainfall Forecasts is defined regionally. A nationally consistent approach is required to define a nationally consistent product.
- The Agency requires a nationally consistent means of routinely assessing and analysing the accuracy of rainfall actuals and forecast (QPF) products by location/storm type/magnitude etc. (This could be developed in conjunction with the Met Office.)

With respect to the second point, the Met Office’s stated aim for rainfall observations for flood prediction (e.g. see Golding, 2000) is noted, viz: *“…an accuracy of ±25% at a spatial resolution of 0.5 km and a temporal resolution of 1 minute.”* (Note – strictly speaking Golding means an error of *±25%).* However, this level of accuracy derives from a perception of the need for distributed modelling of urban drainage systems. Not only is this application not the responsibility of the Agency, but, as Golding admits, such performance may exceed the limits of what can realistically be measured. But the point is made – the Met Office does not yet know what accuracy and resolution the Agency requires in rainfall forecasts.

Furthermore, it is noted that the Agency is not currently well placed to understand its own rainfall forecast requirements when: (i) there is no standard mechanism for quantitatively assessing the quality of forecasts provided by the Met Office[3] and (ii) when the Agency does not have a framework for assessing the impact of errors in rainfall forecasts (or even measurements) on its operational procedures (including flow forecasts), although the Agency and Met Office have recently created a new position for Post Event Analysis.

The study highlighted significant shortcomings in the accuracy of rainfall forecasts, yet it is not clear whether these errors would be significant in terms of the operational use of the data. In addition, the scoring system developed and applied is simplified and somewhat subjective and needs further development.

Issues reported by specific regions

Appendix D discusses recent feedback from the regions regarding problems and issues with the availability or accuracy of rainfall data and forecasts and these are summarised in Table 7.6. As noted in Appendix D, some of this review work was based on discussions conducted over the past two years so, in some cases the situation may have improved since the comments were made.

[3] The Met Office does conduct studies into the accuracy of rainfall forecast performance, but these assessments are undertaken at the product supply side rather than to meet the needs of specific users. Assessments also tend to be conducted on an *ad hoc* and selective basis, using performance statistics (PoD, RMSF etc) that are not tailored to the needs of the Agency. Further information is provided in Section 6.1.3.

Table 7.6. Regional issues regarding radar rainfall data and forecasts (mid-2000) (Adapted from National Weather Radar Strategy, 2000)

Region	Use in forecasting
Anglian	Coverage is poor in parts due to the size of the region relative to radar location. Radar coverage is poorest in east of region.
Midlands	Clee Hill data are poor over the Welsh mountains due to orographic growth/development of rainfall below the beam. There is also a blockage in the radar signal caused by local buildings to the west of the radar resulting in underestimation over a small sector. Ingham data are used primarily for the urban areas of East Midlands but these are long range (low accuracy) for this radar. Radar estimates could be improved using the Region's extensive network of 0.2mm tipping bucket rain gauges or Nimrod data.
North East	Hameldon Hill radar poor on the eastern side of the Pennines due to beam blockage and the height of the beam. Hameldon data are adjusted locally and fed into forecasting models at the discretion of the Forecasting Duty Officer. There is inadequate coverage of Northumbria at present. The Ingham radar can only 'see' up to the lower end of the Ouse basin. Resolution of convective storms is regarded as poor and data are regarded as qualitative only. A radar in a more central location within the Region would increase regional usage and acceptance.
North West	Radar coverage is generally good. Accuracy problems can arise in radar predictions for Cumbria as some locations are in sectors affected by beam blockage whilst others suffer orographic enhancement (clouds rising over the fells result in more rain than shown on radar. Thunderstorms can be a problem particularly in the urban areas around Manchester, for example. Forecasting would be difficult due to its localised nature but effort is being put into at least being aware that it is going on (by radar accumulation and GIS).
Southern	Rainfall radar is considered very important, although its use in the Region has been limited until recently because the coverage in parts was not good. It has only been possible to obtain the 5 km^2 data and even this was patchy. The coverage issue is being addressed by the installation of a new weather radar in southeast England.
South West	Catchment rainfall totals are derived from the regional forecasting system. These totals can be displayed and fed into for rainfall runoff models for forecasting sites. All rainfall runoff models are currently calibrated using rain gauge data due to concerns regarding the quality of radar data. At present, forecasting models are being developed for Devon and Cornwall although high resolution actuals and forecasts are required for increased use of radar data and products for Real Time Modelling.
Thames	Radar data are considered very important and the Region has worked with the Met Office to improve accuracy. Nimrod data is received with forecasts from one to six hours ahead. Locally adjusted radar predicts rainfall two hours ahead, and basically predicts the movement of rain over the period through advection GANDOLF has been developed by the Met Office and Thames for convective rain (such as in thunderstorms) and an improved version is now part of the Nimrod system. It forecasts 3 hours ahead – alerts are received every 5 minutes. Rainfall runoff models are currently run off line, with the intention of using them in real time for 21 sites in the near future.
Wales	Weather systems pick up moisture from the Irish Sea which is poorly monitoried by radar. Orographic enhancement is particularly severe over the Welsh mountains which again means that radar may underpredict rainfall. Rain gauges will often measure heavy rainfall without the Met Office issuing a Heavy Rainfall Warning. The Region recognises the potential value of radar in providing forecasts of rainfall, however its use at present is limited for a number of reasons. Radar coverage is poor in certain parts of the region, especially North Wales and parts of the Welsh valleys and it is considered that its accuracy in South Wales is poor. The Southern Areas do not receive Met Office forecasts on a regular basis.

Discussion of specific issues

Having set the general context for the operational problems faced by the Agency, it is now worth elaborating on some of these issues in more detail. The topics discussed are:

- Use of rainfall forecasts with lead-times up to T+6 hours
- Use of rainfall forecasts having lead times from T+6 to T+36 hours
- Forecaster training
- Post event forecast performance analysis
- Systems for displaying and archiving weather radar data
- Use of probabilistic/ensemble rainfall forecasts
- Impact of changes in radar data processing algorithms

a) Use of Rainfall Forecasts with lead times up to T+6 hours

There are three systems currently in use within the Agency for forecasting rainfall at short lead times: Nimrod, Hyrad (e.g. Thames, North-East and Anglian regions) and Gandolf (used by Thames region on a trial basis). At present, only the South-West and Midlands regions are known to routinely use Nimrod forecasts quantitatively as a direct input to rainfall-runoff forecasting models whilst the RFFS operated by the North-East region possesses the capability to use rainfall forecasts generated by the Hyrad system.

The Midlands Region have been using Nimrod forecasts routinely for three years in conjunction with their flow forecasting models and have reported the following specific issues:

- it is difficult to ascertain whether errors in flood forecasts are due to errors in Nimrod rainfall forecasts or shortcomings in the hydrological model.
- there is uncertainty as to whether there is time to wait for a nowcast before issuing a warning. The balance between maximising warning lead-time and forecast accuracy is complex and involves many factors including: catchment response time (time to peak); projected rainfall intensity; catchment antecedent conditions etc.
- An important use for Nimrod forecasts is in assessing when rain is likely to cease falling. This is important in both the estimation of accumulations and also the preparation to issue all-clear notices, although it should be noted that all-clear notices are not issued until rivers have dropped below the flood warning level.

Regarding Gandolf, one of the primary restrictions for Agency use (and, more generally, the use of other forecasting techniques for convective rainfall) is the inability to forecast prior to the onset of the rain. The delay between onset of convective rainfall and the accumulation of a precipitation total that can cause a flooding incident (particularly in urban areas) is so small that there is no time to respond effectively once the convective storm has initiated. An R&D project is proposed to help address this shortfall.

Also, since the Met Office Nimrod forecast products are produced on a 15-30 minute cycle, there is a limit to how early convective precipitating systems can be observed and how their development can be monitored. Thunderstorms have lifetimes of the order of 30 minutes and in that period can produce significant quantities of potentially flood producing rainfall. The 15 minute temporal resolution of Nimrod is not adequate to observe these storms and accurately estimate the quantity of precipitation they produce. This does not aid flood forecasting.

b) Use of rainfall forecasts with lead times from 6 – 36 hours

Heavy Rainfall Warnings are provided for predefined (sub-regional) areas. The number of areas in a region varies (e.g. there are three in Thames, seven in North-East, and eight in the Midlands) and the size of the areas may vary significantly within a region. The areas are not necessarily catchment based. Further information is provided in Section 4.2.

A number of regional offices use forecasted rainfall triggers which, if exceeded, may lead to a Flood Watch being issued. The approach developed in the Midlands Region (and used elsewhere) of a simple contingency table combining forecasted rainfall with soil moisture deficit, to set levels for issuing Flood Watch conditions (see Table 7.7) is worth noting. However, there is often some reluctance to issue a Flood Watch based on this evidence alone, and issuance is often left until significant rainfall is actually observed.

At present, the accuracy of rainfall forecast products at this lead-time is not felt by the Agency to be sufficient for confident quantitative use in rainfall-runoff forecasting models, although some regions have nevertheless developed a capability (as an example, the North-East Region disaggregates six 6-hour rainfall forecasts for a 36 hour period to rainfall depths distributed over 15 minutes periods).

The following observation by Golding (2000) is relevant. He notes that: "*Despite significant increases in computing power over the past three decades, real-time operational NWP models still have coarse resolution relative to the scale of precipitation features*" and also that, "*NWP models can only realistically represent features extending to at least four grid intervals except where there is very strong forcing from the surface*[4]"

For the current Met Office mesoscale model, this sets a minimum scale of 50 km (for most situations). Clearly, reducing the areas over which rainfall forecasts are provided by the existing mesoscale model to anything below 50 x 50 km may compromise the accuracy of the rainfall forecasts. Furthermore, any reduction in the size of the areas defined for NWP model derived products such as Heavy Rainfall Warnings will need to be linked with a reduction in the grid length of the mesoscale model. It is noted that some of the areas defined by the Agency are already smaller than this recommended minimum size – this would go some way to explaining the experience of the Agency regarding the performance of Heavy Rainfall Warnings.

Temporal resolution as well as spatial definition also limits the quantitative use of the rainfall forecasts for flood forecasting. It was noted earlier that the local mesoscale NWP model provides estimates of rainfall depths at a temporal resolution of 1 hour, updated every six hours. This information is not available to the Agency and although there is no technical reason why the Agency should not receive such a product, it is felt unlikely that the additional expenditure would be justifiable whilst the spatial resolution of the product is limited to 50 x 50km.

[4] Later in his paper, Golding comments that weakly forced rain belts frequently affect the UK in the summer months.

Table 7.7. Floodwatch Contingency Table – Midlands Region Severn Catchment

Area for Flood Watch Assessment		Next 24 hrs worst case rainfall				SMD	Flood Watch Criteria SMD				Criteria Met? SMD/RAIN				Flood Watch Y/N
		6hr	12 hr	18 hr	24 hr		<5	5 TO 20	21 TO 40	>40	<5	5 to 20	21 to 40	>40	
Upper Severn															
US1	North Powys area	3.8	5.8	8.8	10.8	39.0	20mm in 6 hrs or 25mm in 12 hrs	25mm in 6 hrs or 30mm in 12 hrs	30mm in 6 hrs or 40mm in 12 hrs	30mm in 6 hrs or 45mm in 18 hrs	NO	NO	NO	NO	**NO**
US2	North Shropshire	3.0	5.0	8.0	10.0	50.3	24mm iin 6 hrs or 30mm in 12 hrs	28mm in 6 hrs or 35mm in 12 hrs	32mm in 6 hrs or 40mm in 12 hrs	35mm in 6 hrs or 45mm in 18 hrs	NO	NO	NO	NO	**NO**
US3	South Shropshire	3.0	5.0	8.0	10.	50.8	24mm in 6 hrs or 30mm in 12 hrs	28mm in 6 hrs or 35mm in 12 hrs	32mm in 6 hrs or 40mm in 12 hrs	35mm in 6 hrs or 45mm in 18 hrs	NO	NO	NO	NO	**NO**
US4	The Black Country and North Worcestershire	2.0	4.0	6.0	8.0	50.3	18mm in 6 hrs or 23mm in 12 hrs	20mm in 6 hrs or 25mm in 12 hrs	25mm in 6 hrs or 30mm in 12 hrs	25mm in 6 hrs or 30mm in 12 hrs	NO	NO	NO	NO	**NO**
Lower Severn															
LS1	Upper Avon Valley	2.0	4.0	6.0	8.0	63.1	10mm in 6 hrs or 13mm in 12 hrs	13mm in 6 hrs or 18mm in 12 hrs	18mm in 6 hrs or 23mm in 12 hrs	20mm in 6 hrs or 28mm in 12 hrs	NO	NO	NO	NO	**NO**
LS2	Lower Avon Valley	2.0	4.0	6.0	8.0	60.3	15mm in 6 hrs or 19mm in 12 hrs	18mm in 6 hrs or 23mm in 12 hrs	23mm in 6 hrs or 28mm in 12 hrs	23mm in 6 hrs or 30mm in 18 hrs	NO	NO	NO	NO	**NO**
LS3	Severn Vale	2.0	4.0	6.0	8.0	62.0	12mm in 6 hrs or 16mm in 18 hrs	16mm in 6 hrs or 25mm in 18 hrs	25mm in 12 hrs or 32mm in 24 hrs	35mm in 12 hrs or 40mm in 24 hrs	NO	NO	NO	NO	**NO**

c) Forecaster training

It is generally acknowledged that, even with the most sophisticated computer display and modelling systems, a forecaster's knowledge and experience is invaluable for decision making, particularly when information is being received from several sources. One of the recommendations of the Bye Report (Environment Agency, 1998b) was improved training in meteorology for flood warning practitioners. Under the National Weather Services Agreement, the Met Office has developed three bespoke courses for Agency flood warning staff. Of the three courses – two are meteorologically based (see Table 7.8), with a third on tidal forecasting. From 2002 the courses are split into three levels, the aim being to broaden the range of the courses and to cater for EA regional 'forecasters' and area 'warners'.

Agency staff attending the courses report that the training promotes a greater understanding of meteorological reports, better knowledge of the basis of weather forecasts, and increased confidence in interpretation of information.

However, the need for improving the knowledge that flood forecasting staff have of the rainfall information available to them remains. This would improve confidence in the information and allow informed decisions to be made regarding its reliability and applicability in a given situation. In particular, knowledge of the methods used to process the data and the type of errors in forecast rainfall is required. If, in future, error bands are to be included in rainfall forecasts, forecasters should be given guidance on how such information should be used. If rainfall forecasts are to have some probabilistic component then there needs to be clear and continued training in the interpretation of these forecasts and how they can be used with flood forecasting models.

Table 7.8. Met Office training courses available under the NWSA

Course title	Aim and objective	Sessions
Introduction to Meteorology (1 day)	To provide a basic knowledge of the science and practice of meteorological forecasting within the Met Office and to encourage interest and enthusiasm for the subject, and particularly to relate the principles to operational practice in the Agency.	What causes the weather and climate? Air masses, Clouds, Fronts, Depressions, Winds, Rain processes, enhanced rainfall, orographic effects, thunderstorm and lightning, snow situations, data collection (including radar), forecasting methods, computer models, weather forecasting by computer, forecasting charts
Introduction to Radar Hydrometeorology	To provide a basic knowledge of the science and application of radar meteorology in the UK and to encourage an interest and enthusiasm for the subject, and particularly to relate the principles to operational practice in rainfall and flood forecasting	Why use a radar, how does a radar work, the radar equation, calibration methods, the radar wavelength, single site and radar networking, multi parameter and Doppler systems, beam filling, ground clutter, anaprop, bright band, vertical reflectivity profile, advection methods, Nimrod, Gandolf, NWP, new developments, case study

d) Post Event Forecast Performance Analysis

It is recognised that post-event performance analysis is difficult and time-consuming and operational flood forecasters often do not have the time or facilities to undertake such studies. However, it is a weakness of the Agency that so little analysis of forecasting performance is undertaken. This restricts the opportunity to learn and develop good practice throughout the Agency with regard to the effective use of rainfall information. Questions such as 'if the rainfall forecast had been input into the hydrological model at this time would there have been a benefit?' could be addressed. Also, due to the differences in software and hardware platforms, inter-comparison of different systems used within the Agency cannot be undertaken easily.

There also appears to be a requirement for an objective assessment of the value of the systems and procedures used in different regions during particular events. As a precursor to this case study data must be archived. This would include recording all data that was available to the forecasters and the time of availability, how it was used, the forecasts made and the outcome of the event. Any hydrological model runs made, whether results were employed or not, should also be archived.

e) *Systems for displaying and archiving weather radar data*

At present, regions use a range of systems for displaying and archiving weather radar data. These systems can display a range of radar rainfall products, replay time sequences of radar frames, generate rainfall accumulations at a range of spatial scales, and even include rainfall forecasting algorithms.

At present, the linkage between these systems and hydrological forecasting models (e.g. rainfall-runoff models) is not fully exploited and (with some exceptions) rainfall forecasts are not fed operationally into flow forecasting models. In particular, a problem remains in discriminating the errors in hydrological models from those in rainfall forecasts, and in dealing with missing data (some systems use a hierarchy of preferred data sources, including radar data, rain gauge data, manually entered data and back up 'typical' profiles).

Although some individual systems (e.g. WRIP) have facilities for locally archiving radar data, the Agency has no comprehensive, nationally consistent strategy for archiving radar rainfall observations and forecasts and hydrological data, or standard formats for interfacing radar data and forecasts to hydrological models. Therefore there is very limited analysis of how data was used in particular flood events. Some archiving of rainfall actuals and forecasts is undertaken by the Met Office for its own purposes, usually on an event basis, and a system for improved archiving and retrieval of Nimrod actuals is currently under development. However, the Agency does not yet have access to this archive data, and events are not always complete.

In some cases, perhaps, there have also been problems with the long term support of radar display systems with the original developers unable to fund improvements to the system or not being able to provide the required level of system support. Some regions have overcome this problem through development of a system in-house (e.g. Thames regions CASCADE system).

f) *Use of Probabilistic/Ensemble Rainfall Forecasts*

The Agency is still to form a nationally consistent view on the requirement for some measure of confidence in forecasts, both of rainfall forecasts and level/flow forecasts. On the one hand there is a pragmatic desire for a single definitive rainfall forecast for input into flow forecasting models, whilst on the other, it is recognised that rainfall forecasts are inherently uncertain, and that it is only sensible to acknowledge this through the production of ensemble flow forecasts and (hence) forecast uncertainty bounds or confidence limits. The Met Office is now using ECMWF ensembles to notify forecasters of potential severe weather to improve forecast lead-times as part of the First Guess Early Warnings system. The system is currently in a relatively early stage of its development and further assessment of its potential and performance is required as part of its ongoing development.

g) *Impact of changes in radar data processing algorithms*

The Agency needs to be aware of changes in radar data processing algorithms and hardware and the impact of these changes (within the context of this project) on real-time flood forecasting.

To illustrate, improvements in the accuracy of radar rainfall estimates through the introduction of new or improved adjustment methods may significantly change the characteristics of the rainfall actual and/or forecasts (e.g. through a reduction in mean field bias). Rainfall-runoff forecasting models calibrated using earlier data time series will implicitly contain model parameters estimated to minimise flow forecasting errors arising from bias in the rainfall field, and, as such, may be inappropriate for use with the improved rainfall field and require re-calibration.

It is therefore important that the Met Office and Agency have a continual dialog regarding changes to any processing procedures that may impact on the radar rainfall products provided to the Agency, and that a date stamped audit trail of processing changes is maintained by the Met Office and available to the Agency.

7.3 General Requirements for use in Flood Forecasting

The discussion so far in this report has considered the various types of data and forecasts available, and how they are currently used for operational flood warning and forecasting, together with some of the problems which are encountered.

A different perspective can be obtained by considering - from the point of view of monitoring and forecasting floods - what rainfall information would ideally be available. Obviously, the requirement varies depending on the size and nature of the catchment, and the type of rain generating events under consideration (convective, frontal etc). This section considers the requirements reported by Agency staff in recent consultation exercises together with some results from recent research studies on this topic.

An alternative view of the problem is to consider the size of catchment and storm, and catchment response times, for which rainfall data and forecasts would significantly add to the ability to forecast flood events. A widely quoted 'rule of thumb' (Reed, 1984) is that rainfall measurements and forecasts are of most use in catchments in which the lag time (between rainfall events and forecast points) is less than about three hours, with flow routing preferred for times of more than nine hours. In between these times, there is an intermediate zone (3-9 hours) in which there is a trade off between issuing more accurate (but later) warnings based on flow routing, or earlier but less accurate forecasts based on rainfall runoff models (using either real time rainfall data or rainfall forecasts). It must be emphasised that these are all approximate figures and will vary between catchments, storm types/size etc.

Forecasters can also possibly be presented with a range of forecasts e.g. using radar data alone, rain gauge adjusted radar data, rain gauge data alone, and rainfall scenarios (e.g. no future rain, or typical profiles). Regarding the size of storm, when the spatial scale of the meteorological event is significantly less than the spatial scale of the catchment, forecasting becomes more difficult requiring distributed catchment models and the ability to resolve rainfall distributions over smaller areas. The choice between radar and rain gauges will depend on the catchment size, the number of forecasting points and the ability of the radar (and rain gauge network) to cover the catchment area. Attempts have been made to develop general guidelines on the required densities of rain gauges for flood forecasting applications but this remains very much a research area since results (at present) are so dependent on the location and the nature of the catchment and the type of flood generating storm.

7.3.1 General considerations

Consultations with Agency staff, presented fully in the Real Time Modelling Technical Report, identified the following key forecasting problems:

- fast responding catchments;
- flood levels at or near confluences;
- the influences of structures;
- catchments with significant floodplain storage;
- the influence of groundwater;
- low benefit locations;
- the combined influence of rivers and tides;
- urban catchments;

- locations with reservoirs upstream;
- complex channel networks.

Lack of data was not considered as a forecasting problem although it is recognised to be a pressing issue in many circumstances. Although rainfall data and forecasts can have a role in all of these situations, areas in which they are particularly important include:

Fast Response Catchments

The most common problem, identified by the majority of regions, is forecasting in fast response catchments. In England, the Agency aims to provide a minimum two-hour warning of flooding to all properties at risk from flooding in flood warning areas where technically feasible: In Wales this lead-time can be reduced to one-hour by derogatory powers. For catchments that respond rapidly to rainfall this is difficult because times to peak are short, therefore a rainfall-runoff forecasting approach is required to provide a sufficient lead-time for flood warning, possibly with short-period rainfall forecasts to further extend forecast lead times. However the Agency notes that many fast responding catchments may have poor quality rainfall data or inadequate coverage by radar and/or rain gauges.

Urban Catchments

Urban catchments are characterised by high runoff rates and a fast response to rainfall, often over small catchments with areas of a few square kilometres. It is also difficult to predict the timing and magnitude of surface drainage and the watercourse may be affected by structures and flood defence schemes. However, these areas are critical since they are the densely populated and therefore display the highest cost-benefit ratios. Ideally, data and forecasts should be received at much shorter intervals than in larger catchments (e.g. a few minutes).

Reservoired Catchments

The storage and operation procedures of reservoirs upstream of risk areas can make the forecasting of timing and magnitude of the peak flows difficult. In order to model reservoirs correctly, rainfall-runoff models are required to predict reservoir inflows, control rules relative to reservoir level are required to model outflow and a water balance model is required to determine the level in the reservoir relative to inflow and outflow.

7.3.2 Recent Agency consultations

Section 7.3.1 presented some general considerations regarding the use of rainfall data in specific situations. The Rainfall Collaboration Project (Met Office, 2001b) reported specific requirements identified by Agency staff for rainfall data for a number of applications, including flood warning and forecasting, and these are summarised below.

General requirement

Flow forecasting is potentially rainfall data hungry, requiring sub-daily rainfall information in real-time for use as an input to rainfall-runoff models. All regions, without exception, regard real-time sub-daily rainfall data as being essential for flood forecasting. In practice, this necessitates the provision of tipping bucket rain gauge (or weather radar) data linked to the central forecasting system by telemetry. The coverage of telemetered raingauge data within the Agency has improved greatly as a result of hydrometric improvements initiated after the Easter 1998 floods, and additional Met Office raingauges becoming available through the Rainfall Collaboration Project. However, new models, and upgrades to existing models, are still required to take advantage of this new real time information.

Spatial resolution

The spatial resolution required varies according to the size of the catchments being modelled. This varies considerably, but is typically in the range 10 – 200 km^2 with a mean value of approximately 75 km^2. Catchment rainfall totals are usually calculated from the tipping bucket rain gauge data using an automated Theissen polygon approach – the estimates so derived improving in accuracy with increasing network density. Many catchments modelled using rainfall-runoff models are at the upper end at relatively high elevations, and the need is therefore for sufficient information on the spatial variation in the rainfall field at these elevations. One of the Bye Report recommendations was also that Regions should be able to access data from neighbouring regions

Daily rainfall data

Extensive use is also made of daily rainfall totals, usually to update the state of the internal variables of the forecasting models to ensure that the antecedent conditions are accurately represented by the models. However, this information will still be required in real or near-real time. Almost without exception, the root mean square error of daily rainfall totals was cited as 10% of true rainfall. This figure was consistently quoted by all regions and for all applications.

Snowfall/snowmelt

The general operability of rain gauges in snow and the measurement of water equivalent of snow did not arise during the consultation exercise. However, the influence of snow cover (storage medium when temperatures are below freezing) and the impact of the release of potentially large volumes of water when temperatures rise (snow melt) on hydrological systems can be significant – *in extremis* causing severe flooding. It is therefore important that the operability of rain gauges susceptible to snow cover (predominantly the upland areas of England and Wales) is considered when a network is reviewed or new installations considered, and other methods of detecting snow cover (e.g. satellite images) to complement the information provided by manual observing stations. Additional information on snowcover and snowmelt is provided in Section 2.4.

Sub-daily data

The accuracy of tipping bucket rain gauge measurement of rainfall at medium to high intensities was also investigated by the Rainfall Collaboration Project. The prime focus of attention was underestimation at high intensities, and the correlation between rainfall intensity and underestimation in recorded totals. Regarding the required accuracies reported by the regions, again (as for daily rainfall data), a maximum acceptable error of 10% was cited by all eight regions.

As part of this exercise, the Met Office was also consulted on its requirements for adjusting products such as Nimrod and running numerical weather prediction models and the main results are summarised in Table 7.9.

7.3.3 Recent research results

The results cited give an indication for the required temporal and spatial accuracy for rainfall measurements (and, by implication, for rainfall forecasts). However, this topic is an active research area – in the UK and overseas. For example, the results from a recent German study by the national flood warning service (see Section 5.4) has, in consultation with practitioners, produced an application matrix detailing the requirements for rainfall observation and forecasts for a range of uses (Einfalt, 2001). This matrix is reproduced in Table 7.10. Whilst some of the requirements require further explanation, it is interesting to note that users expect rainfall products at 10 km resolution every 5 minutes for flood warning purposes. The Met Office is moving toward a similar temporal resolution, but has primarily concentrated on increasing spatial resolution of radar rainfall products.

Table 7.9. Summary of Met Office requirements for rainfall data (Source: Met Office, 2001a)

Application	Data Required	Timeliness	Comments
Radar Calibration	Hourly totals	Real-time	30 km spacing within 100 km radius of radar
General Forecasting	Hourly precipitation intensity, amount and type	Real-time	100 km spacing plus additional observations where topography is complex
NWP	Hourly amount, rate and type	Real-time	50 km spacing, 20km spacing desirable
Nimrod	Hourly totals	Real-time	50km spacing
	Precipitation type detection		20 km spacing, 5 minute reports desirable
	Sub hourly rate and amount		20 km spacing, 5 minute reports desirable
Climatology	Hourly/sub-hourly totals	Slow time	From at least 10 sites across UK
	Daily totals	Slow time	20km spacing
	Monthly totals	Slow time	20 km spacing but greater density where topography is complex
Media Enquiries	Hourly totals	Real-time	Mainly focussed on urban areas
International Exchange	6 Hourly totals	Real-time	From the 150 km spaced RBSN network of stations defined in UKON1
	Monthly totals	Slow time	
Research	Daily totals	Slow time	10 km spacing
	Sub hourly totals	Slow time	Greater density in upland areas
Climate Change	Daily and Monthly totals	Slow time	Groups of long period stations
Commercial summaries	Hourly and daily totals	Near real-time	To be generally representative of major urban areas (>100 000 population)
Sewer Flooding Events	Sub hourly data	Near real-time	Representative of urban areas
Business Enquiries	Rainfall intensity (sub hourly)	Slow time but near real-time desirable	Representative of urban areas
	Daily totals		10 km spacing essential, 5km desirable, especially in urban areas
	Hourly totals		20 km spacing, especially in urban areas
MORECS	Daily totals over 40x40km areas	Near real-time	One daily gauge per 40 km grid square

Table 7.10. German user requirements for rainfall data (adapted from Einfalt, 2001)

Application matrix	Spatial resolution [km]	Temporal resolution [minutes]	Volumetric resolution [mm]	Forecast lead time [hours]	Max. time lag for data arrival [minutes]
Rainfall runoff models	0.1	1	0.1	-	-
Flood forecasting	10	5	1	72	15
Flood warning	10	5	1	72	15
Hydraulic simulation	1	5	1	-	-
Insurance 'proof of event'	1	1	1	-	-
Control of basins and reservoirs	5	15	1	48	5
Sewer system simulation	0.1	1	0.1	2	5
Determination of design values				-	-
Areal rainfall (monthly and yearly values)		-	1	-	-
Personal organisation during flood periods	10	15	1	48	5
Flow measurement service	10	5	1	12	15
Detailed information on extreme events	1	1	1	-	-
Decision support for planning purposes				-	-
Operation of waste water treatment plants	10	5	0.1	48	5
Determination of fees for rainwater			0.1	-	-
River basin management	10	15	1	-	-
Research	1		0.1	-	-

8. OPTIONS APPRAISAL

8.1 Introduction

As a result of the studies described in this report, a total of 33 potential R&D topics have been identified to address existing shortfalls in current Agency practice have been assessed and prioritised on the basis of the need of the Agency and are described in Section 8.2.

The outcome has been the identification of twelve high priority R&D topics (Section 8.3). These twelve have been categorised either as 'Class A' or 'Class B' topics – the former being regarded as the highest priority, with the latter ranked slightly below. The Class A and B topics are presented in the form of draft Short Form A's in Appendix F.

8.2 Possible R&D topics

The 34 candidate R&D topics are categorised using the following headings: (i) weather radar; (ii) rain gauge measurements; (iii) rainfall forecasts; (iv) flood forecasting issues. Each topic heading is further sub-divided.

8.2.1 Weather radar – coverage and accuracy

a) Improving adjustment techniques which use models of the Vertical Profile of Reflectivity and the outputs from numerical weather prediction models, and supported by the use of multi-beam scanning radar data and (possibly) vertically pointing radars

b) Using dual polarised radars to gain more information on attenuation, identification of hail, bright-band identification and correction etc

c) Improving adjustment techniques using real time rain gauge data, and assessing the network density of rain gauges required in different situations, particularly upland and urban areas (a project "Improved rainfall accumulations" is already underway to address some of these issues with the focus on improving Nimrod daily rainfall totals).

d) Re-examination of the use of higher elevation scans in radar correction

e) identification of the inception of convective events

f) Investigation of new techniques to estimate rainfall deduced from the signal attenuation measured along microwave communication links

g) Investigations into the feasibility of developing low cost, short range, possibly mobile, weather radar outstations using mainly off the shelf products (e.g. aviation radar) for deployment in or near flood prone catchments.

h) Refinement of cost benefit analysis techniques for reviewing weather radar network coverage which builds upon current approaches to consider the national benefit to rainfall observation/forecasting as well as site specific/population at risk issues

8.2.2 Weather radar – display and analysis systems

a) Scoping study for possible future improvements to existing display systems to allow GIS presentation of data, internet access to data, multiple views (cross sectional, 3D) of rainfall areas etc, real time archiving (see later) and development of national standards for interfacing radar data and products with flow forecasting models

8.2.3 Rain gauge measurements – tipping bucket measurements

a) Investigations into the resolution and accuracy required for tipping bucket and storage rain gauges when used for flood forecasting applications (and how measurement and area averaging errors propagate into level/flow estimates; see later)

b) Investigation of new high resolution techniques for measuring rainfall including experience on the HYREX project and in New Zealand

8.2.4 Rain gauge measurements - Other issues (snowfall, storage gauges etc)

a) Observing snowfall, including use of satellite imaging to detect snow cover and snowmelt algorithms.

8.2.5 Rainfall forecasts – general

a) Research into rainfall forecasting techniques specifically for slow moving systems

b) Integration of the Met Office Gandolf/CDP thunderstorm forecasting methods into the Nimrod rainfall forecast system (first phase in progress with a basic Nimrod+Gandolf 2 km product implemented in June 2001).

c) Development of a storm scale (1 km resolution) Numerical Weather Prediction model and review of its application to flood forecasting.

d) Detailed specification of the Agency's requirements for rainfall forecast products (accuracy, spatial resolution and lead-time/timeliness?) through case studies, modelling, international reviews etc.

e) Development of a consistent framework for assessing the performance of rainfall forecasts from the client side, to support the production of Levels of Service agreements with a rainfall forecast supplier.

f) Development of a nationally consistent means of routinely assessing and analysing the accuracy of rainfall actuals and forecast (QPF) products by location/storm type/magnitude etc

8.2.6 Rainfall forecasts - Heavy/extreme rainfall forecasts

a) Investigations into better ways of using heavy rainfall forecasts in operational flood warning, including the criteria used, presentation methods and use of probabilistic estimates (a project 'First guess early warnings' is already exploring some of these ideas).

b) Investigations into the performance of outputs from the Met Office Numerical Weather Prediction model at lead times of up to 36 hours, and the feasibility of producing a single integrated product for Agency use incorporating the shorter term Nimrod forecasts.

8.2.7 Rainfall forecasts - Short term forecasts (Nimrod, HYRAD etc)

a) Continuing support to initiatives to develop better convective models for operational use, use of more hydrologically appropriate grid scales (e.g. 1, 2 km), improved radar-only forecast models etc

b) Investigations into the practicality of routinely including real time diagnosis of uncertainty in rainfall occurrence, amounts, type etc as one or more fields in Nimrod forecasts for use with flood forecasting models

8.2.8 Rainfall forecasts – ensemble forecasts

a) Investigations into how ensemble forecasts can best be used with flood forecasting models, and how the information can be presented to operational staff, and whether it is practical to run multiple scenarios through hydrological models before analysing the output

8.2.9 Rainfall forecasts – thunderstorm/convective rainfall

a) Research into techniques for detecting the onset of convective storms in clear air, including Doppler radar, satellite imagery, near surface humidity measurements, NWP output and neural networks

b) Investigations into the feasibility and cost and other implications of producing Nimrod products at 5 minute intervals

c) Investigations into techniques for detecting, modelling and displaying the internal structure of storms using radar and other methods

8.2.10 Flood forecasting issues - Using rainfall data/forecasts with hydrological models

a) Assessment of the use of Nimrod and/or other rainfall forecast products in operational flood forecasting models over one or more flood seasons (It is noted that a 12-month project 'Optimising Nimrod for Flood Prediction' is already under consideration and may partially address this research need.)

b) Investigations of the propagation of errors in rainfall data/forecasts into the outputs from hydrological models using case studies and/or synthetic data

c) Investigations into future 'ideal' targets for accuracy and temporal and spatial resolution of rainfall data for flood forecasting applications and for analysing and displaying uncertainty associated with rainfall and flow forecasting models

d) Detailed review of international practice and experience in using rainfall data/forecasts in flood forecasting, and practice/experience in related fields in the UK e.g. operational management of urban drainage/sewerage systems

e) To assess the use of the MOSES data product for real-time flood forecasting for a range of catchment scales, storm types and antecedent conditions. Investigate the feasibility of integrating the output from the Met Office MOSES system into the EnviroMet® system to provide a GIS functionality involving surface moisture, likelihood of convection rainfall forecasts, catchment boundaries and DTM information

8.2.11 Flood forecasting issues – data archiving and post event analysis

a) Specification of the requirements for real time data archives for flood forecasting applications, capable of storing the information known at each time interval (for subsequent post event analyses, training etc)

8.2.12 Flood forecasting issues – training

a) Development of internet and multimedia training tools for flood forecasting staff, and decision support and expert systems to support operational staff

8.3 High Priority R&D topics

As part of this project, the 33 possible projects were assessed using a simple scoring system. Also, any overlap with ongoing Met Office and other research projects was identified. The outcome of this exercise was a set of 12 high priority R&D topics as listed below (with Section 8.2 reference in parenthesis). Further information on the topics is presented in Short Form A format in Appendix F.

'Class A' Topics

A1. Slow Moving Rainfall (8.2.5[a])
A2. Agency's Target for Rainfall Forecasts (8.2.5[e])
A3. Post Event Assessment of Rainfall Forecasts (8.2.5[f])
A4. Onset of Convective Storms (8.2.1[e])
A5. Propagation of Errors in Rainfall Forecasts into Flood Forecasts (8.2.10[b])
A6. Training Tools and Decision Support Systems (8.2.12[a])

'Class B' Topics

B1. Use of MOSES for Flood Forecasting (8.2.10[e])
B2. Using Heavy Rainfall Warnings (8.2.6[a])
B3. Better Convective Storm Models (8.2.7[a])
B4. Using Ensemble Forecasts (8.2.8[a])
B5. Assessment of Nimrod Forecasts for Real Time Modelling (8.2.10[a])
B6. Real Time Archiving (8.2.11[a])

9. CONCLUSIONS AND RECOMMENDATIONS

This report has reviewed the current situation regarding the availability and use of rainfall measurements and forecasts in flood forecasting in the UK and elsewhere. This has included an assessment of the advantages and limitations of each approach leading to the following general conclusions concerning recommended future R&D and other requirements.

a) R&D/operational. Guidelines, training, decision support. The guidelines identify best practice in the use of rainfall measurements and forecasts, and this technical report discusses the current situation. It will be an ongoing Agency task to update the guidelines to take account of new developments and there is also a potential R&D need to develop intranet and multimedia training tools for flood forecasting staff, and decision support and expert systems to support operational staff.

b) R&D/operational. Post Event Assessment of Rainfall Forecasts (and Actuals)/ Real Time Archiving. This project has identified post event analysis/data archiving as a key issue and has recommended techniques which might be adopted nationally following evaluation by Agency practitioners. Further work will be required to devise operational procedures for applying these techniques, archiving of the results (raw data and interpreted values), interpretation of the results and their implications for Real Time Modelling, and dissemination of this information to interested parties (practitioners, the Met Office etc). Note: the new Agency/Met Office post event analyst appointment may address this need and the following R&D recommendation also addresses this issue.

c) R&D. Agency's Targets for Rainfall Forecasts. Further work is required to assess the Agency's requirements for rainfall actuals and forecasts both spatially and temporally for common types of flood forecasting problem e.g. by catchment type (urban etc), storm type (e.g. convective) and lead time-both through analysis of past success rates in forecasts and issuing flood warnings (post event analysis), and research into the requirements of the categories of rainfall runoff models used in real time flood forecasting.

d) Implications of new products. A number of new meteorological products are currently becoming available with high potential for improvements to Real Time Modelling/flood forecasting following evaluation by the Agency. These include software systems (e.g. NIWRDS), Met Office products (e.g. MOSES, high resolution Nimrod data, locally adjusted Nimrod) and the findings of ongoing research and post event analysis. It will be a continuing Agency task to evaluate these products as they become available, to assess their uses in Real Time Modelling through R&D and operationally, and to make practitioners aware both of the potential benefits and the implications for the calibration/operation of existing Real Time Models (e.g. the need for recalibration).

e) R&D. Slow Moving Rainfall. To develop methodologies for assessing the flood risk and impact of slow moving rainfall events in real time. This might include real-time processing of rainfall actuals and forecasts to provide depth-area-duration information at a range of catchment scales, combined with estimates for catchment conditions (e.g. MOSES), to provide warnings of high runoff conditions. Also, investigations into real time estimation and display of the uncertainty associated with forecasting the development and progression of slow moving storms.

f) R&D. Onset of Convective Storms/better convective storm models. To develop a reliable method for forecasting the onset of convective storms based on improved detection of atmospheric conditions and models of storm development. Also, further improvements in forecasting the development and movement (and hence, depth and location of storm rainfalls) of convective storms: consolidating on recent improvements in forecasting storm development (e.g. though storm life history algorithms) and improvements in the spatial definition of forecasts.

g) R&D. Propagation of Errors in Rainfall Forecasts into Flood Forecasts. To improve understanding of the impact of rainfall forecast errors, for a range of forecast lead-times on river flow (level) forecasts (for a range of forecast lead-times) for different types of rainfall systems (convective/frontal etc), types of flow forecasting model and categories of river catchment (upland, urban, geological type, small/medium/large etc). Note: see the Real Time Modelling technical report also for further results and recommendations and the importance of post event analysis to this work.

h) R&D. Use of MOSES for Flood Forecasting. MOSES has the potential to improve flood forecasting accuracy through the monitoring and updating of soil moisture deficits at spatial and temporal scales commensurate with the requirements of operational flood forecasting as well as underpinning the development of flooding potential maps and in issuing Flood Watches based on threshold tables.

i) R&D/operational. Using Heavy Rainfall Warnings. This project has made recommendations regarding setting alarms and use of Heavy Rainfall Warnings which need addressing by the Agency through training and development of nationally consistent Best-Practice guidelines for the operational use of Heavy Rainfall Warnings.

j) R&D/operational. Using Ensemble Forecasts. To increase the Agency's understanding of the impact of uncertainty in rainfall forecasts on river level (flow) forecasts (and hence, flood warning) and guide the Agency on use of ensemble rainfall forecasts. Note: see the Real Time Modelling technical report also for further results and recommendations.

k) R&D. Assessment of Nimrod Forecasts for Real Time Modelling. To evaluate the use of Nimrod forecasts as an input to rainfall-runoff forecasting models, and to illustrate the accuracy that can be expected and impact of rainfall forecast lead-time on flood forecasting accuracy

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