Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

Extreme Event Recognition Phase 2

R&D Technical Report FD2208/TR

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Statement of Use
This report and its appendices document the outcome of Project FD2208 "Extreme Event Recognition Phase 2" concerned with improving the capability to provide warnings of extreme flood events. It addresses a key flood defence objective: to improve flood warning lead times and thereby facilitate more effective mitigation of flood impacts.

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Executive Summary

This project was commissioned within the Flood Forecasting and Warning theme of the joint Defra/Environment Agency Research Programme and forms the second phase of work investigating ways of improving Extreme Event Recognition lead by the Met Office and including Salford University and the Centre for Ecology and Hydrology (CEH).

The work has focused on achieving a better understanding of Extreme events and their characteristics. The ultimate aim of the work is to enable a better forecasting service for these type of events which can develop very quickly, can have severe consequences and are currently problematic to predict. Phase 1 of the Project reported in August 2002 (FD2201) and made a preliminary examination of historical events together with looking at catchment susceptibility. The principal findings from Phase 1 were that extreme events can be characterised into a number a different types, e.g frontal, convective, orographic depending on the amount and duration of the rainfall.
Phase 1 also identified an archetypal frontal situation that might be used as an indicator of potential extreme events.

This project – Phase 2 is focused on continuing the understanding of extreme events but also developing and trialling possible new ways of forecasting them.

The work was carried out in 5 work packages with the following objectives:

- Extend the historical analysis of extreme events in Phase 1 to more recent and less extreme events.

- Develop and evaluate an extreme event prediction system based on the indicators identified in Phase 1.

- Evaluate an indicator for extreme convective events based on vorticity.

- Develop rainfall datasets using radar and raingauge data from historical heavy rainfall events, enhanced to represent extreme events, and use them to evaluate the extreme event performance of flood forecasting models.

- Establish a User Requirement for a decision support tool in the light of the Phase 1 recommendations and current practice in the Environment Agency

The work was carried out between January 2004 and January 2006. Encouraging results from the development of the extreme rainfall datasets led to a year's extension of work to implement an operational tool that would be incorporated into Environment Agency flood forecasting systems and training in its use for practitioners.

Much of the benefit of this project comes from the investigation of a number of viable but untested hypotheses so as to move forward the body of understanding and science relating to Extreme Events. It is worth noting that the detailed analysis of rainfall records undertaken in this work was some of the first

undertaken for many years and demonstrates a potential gap in research areas. Although not all the approaches looked at in this work resulted in a significant advance in the forecasting of extreme events, the findings have given direction to those areas where further research is most likely to succeed and those that will not.

The principal conclusions resulting from the Phase 2 work are:

This work has undertaken analysis and investigations of data and approaches to improving recognition of extreme events likely to result in flooding. It has to be concluded from the work undertaken to date that, due to their complexity, there are no short cuts to reliable early prediction of extreme rainfall events using simple predictors. The work indicates that improvements to Numerical Weather Prediction models and observing systems over the next five years should result in better resolution and forecasting of the type of situations that result in extreme events, provided there is adequate investment. Flood forecasting and warning systems can now be tested on extreme rainfall events and flood forecasters trained using the datasets produced in this work. Both of these elements should result in improvements in recognition of extreme events and mitigating their effects by provision of better warnings.

Detailed conclusions from the Phase 2 work are as follows:

- Additional extreme events were identified and conform to the characteristics identified in Phase 1.

- Extreme events are not in a distinct distribution from less extreme ones.
    - Orographic events have the clearest association with the source conditions being critical for an extreme event and determined by the wind direction, fetch and source air mass temperature.
    - Frontal events are more likely to be extreme at locations close to and to the North of a low pressure system.
    - Extreme convective events are distinguished from less extreme ones primarily by the length of the rainfall event rather than its intensity.

- The predictors identified in Phase 1 (e.g. the combination of characteristics that was associated with extreme frontal rainfall) do not provide an adequate basis for predicting when a heavy rainfall event will be extreme. However, for orographic and frontal events, they did show limited skill which is worthy of further investigation.

- The proposed vorticity indicator cannot provide useful information relating to extreme precipitation events except at model grid lengths of 1km or better, which are not available in atmospheric models currently used for forecasting.

- Storm data of convective, orographic and frontal type from historical cases were modified in location, scale, magnitude and movement using a new Rainfall Transformation Tool, so as to create flexible datasets for the evaluation of hydrological flood forecasting models. It was found that the best data, for flood modelling purposes, were obtained by combining raingauge observations with quality controlled radar data.

- Use of the rainfall datasets was demonstrated using different types of hydrological models. The results revealed possible shortcomings in the model assumptions and improved formulations were investigated where appropriate. Training in the use of the datasets and the testing of operational flood forecasting models has been provided to Environment Agency staff as part of this project.

- A User consultation exercise showed that the current requirement was for a catchment vulnerability map, rather than for a decision-support tool.

As a result of this work the following principal recommendations are made:

- Maximum benefit needs to be gained from Met Office investment in Numerical Weather Prediction (NWP) research: by pressing the case for investment in increased computer power; by seeking, through the Public Weather Service Customer Group, to influence the priority given to flood forecasting in the NWP R&D programme; by commissioning R&D into the optimum use of NWP in support of extreme flood warning; and by implementing forecast and dissemination service developments that pull-through improved NWP into flood warning practice.

- Further research is required to investigate whether the annual & decadal variability in extreme rainfall events observed in both Phases 1 & 2 is related to any factors of the atmospheric general circulation that might be predictable by seasonal and climate prediction models.

- There is a need to develop and pursue a long term strategy to move towards a flood risk management system based on the use of probabilistic forecasts, with the primary indicator for action being risk, not probability. Special attention will need to be paid to situations of high risk and low probability, which are expected to be typical of forecasts of extreme events.

More detailed recommendations are included in the body of the report.

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1 Background

In Phase 1 of the project (Collier *et al.*, 2002; Hand *et al.*, 2004), it was demonstrated that extreme precipitation events showed common characteristics which might facilitate forecasting of their extreme nature. In addition, the implications for Probable Maximum Precipitation (PMP) were investigated and an approach to supporting the flood forecasting and warning process through use of a decision support tool was demonstrated.

The Phase 1 project (Collier *et al.*, 2002) concluded the following.

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

- There are implications of the analysis of extreme rainfall events in this work for estimates of Probable Maximum Precipitation (PMP). Whilst the estimates of PMP provided by the FSR (Flood Study Report) appear inadequate, those inferred by extrapolating the FEH (Flood Estimation Handbook) seem to be overestimates. Given the importance for engineering design of PMP it is necessary to undertake further work to clarify the situation.

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

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

It recommended that further work should be carried out as follows:

- New events should be routinely analysed and tested to see how they fit into the classification of events diagram shown in Figure 14 of the Phase 1 Report, and the conceptual model shown in Figure 15 if they are frontal, which should both be updated if necessary.
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- Met Office Mesoscale Model (MM) NWP outputs can be used to provide details of the synoptic evolution, expected rainfall intensity, accumulation and distribution, updated four times a day. If the forecast outputs from the model suggest that rainfall amounts could be high according to pre-defined criteria, then the forecast could be refined into a warning of possible amount and duration of extreme rainfall by identifying the category of the expected rainfall producing system. Categorisation would involve:-

- Picking out threatening orographic events using the criteria in the Phase 1 Report.
- Identifying slow moving frontal zones (particularly warm occlusions or warm fronts) with high precipitation rates and the presence or not of embedded instability.
- Identifying regions lying close to (within 200 km, say) and to the north and west of the centre of a slow moving depression.
- Identifying regions of showers (embedded in frontal zones or otherwise) with high rainfall rates/accumulations from the MM. Then identifying those that are likely to produce large damaging hail and/or likely to possess multicell characteristics in areas of potential instability, which if released, would produce large amounts of CAPE (Convective Available Potential Energy). The Met Office Gandolf, Nimrod and CDP (Convection Diagnosis Scheme) systems all have methods of determining these criteria, which could be utilised, perhaps probabilistically.
- A joint Defra/Met Office/EA project should be set up with a view to establishing a prototype 24-hour early warning system to be tested on independent data, which should include non-extreme as well as extreme events.

- Recent work at the University of Salford (Sleigh and Collier, 2004) proposes a new method of identifying extreme convective events based upon an analysis of vorticity. This method should be investigated further using MM NWP, and, if possible Doppler radar data.

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

- The training data set given in Appendix A of the Phase 1 Report should be combined with radar data from an extreme event (e.g. the Walshaw Dean storm) to develop a gridded data base for use in hydrological model development.

The present project has attempted to address each of the recommendations listed above from the Phase 1 Report. Note that it did not address the issue raised in the conclusions regarding Probable Maximum Precipitation, which remains outstanding.

2 Aims of the Project – Phase 2

The overall aims of the phase 2 project were to investigate and better predict extreme flood events and to be better prepared to mitigate their impact if and when they occur.

To achieve this, the following objectives were set down.

- To extend the analysis of historical extreme events to more recent and less extreme events, to determine whether the conclusions of Phase 1 still hold, and to investigate whether the extreme set form a population that is distinct, in terms of the indicators identified in Phase 1, from the less severe events.

- To develop and evaluate an extreme event prediction system based on indicators identified in Phase 1 using a Bayesian approach in which the *prior* probability, derived from mesoscale model forecast rainfall, is updated using probability estimates of extreme rainfall based on the indicators identified in Phase 1, computed from mesoscale model or ECMWF ensemble model forecast variables.

- To evaluate a vorticity indicator for extreme convective events based on the recognition of developing symmetry, and then asymmetry, in the field of the tipping term in the vorticity equation using model output data and data from the Chilbolton S-band Doppler radar system.

- To develop spatio-temporal rainfall datasets using radar and raingauge data from historical heavy rainfall events, enhanced to represent extreme events, and use them to evaluate the extreme event performance of flood forecasting models.

- To establish a User Requirement for a decision-support tool in the light of Phase 1 recommendations and current practice in the Environment Agency based on consultation with the practitioner (the flood forecasting and warning staff of the EA).

The full text of the aims is presented in Appendix A.

3 Organisation

Following a call for expressions of interest by Defra in May 2003, the Met Office was tasked with putting together a detailed proposal incorporating input from CEH (Wallingford) and Salford University. The resulting two-year project, submitted in September 2003, comprised five work packages. The work was supervised by a Project Board, chaired by Brian Golding (Met Office) and including Linda Aucott (Defra project manager), Tim Wood (EA), Chris Collier (Salford) and Bob Moore (CEH). Additional members contributed to the Project Board for parts of the project. The full membership is listed in Appendix B.

Work started on the project in January 2004, and the first project board meeting was held on 1 March 2004.

The first work package was carried out by the Met Office in 2004-5 and the final report was delivered in November 2005.

The second work package was carried out by the Met Office in 2004-5. A draft final report was delivered in January 2006 and the final version in May 2006.

The third work package was carried out by Salford University in 2004-5 and the final report was delivered in August 2005.

The fourth work package was carried out by CEH (Wallingford) in 2004-6. An extension to the work was agreed by the Project Board in January 2006 and carried out in 2006. The final report incorporating the R&D work of both parts was delivered in October 2006. Provision of data sets to EA practitioners and training in their use was undertaken in March 2007.

The fifth work package was carried out by the Met Office in 2004 and the final report was delivered in January 2005.

Management documents and reports were shared through a password-protected web page hosted on the Met Office web site.

During the project the members have established and maintained links with other relevant research activities:

- The Boscastle and Carlisle floods occurred during the project and data from these events were included in relevant work packages. The follow-up to those events was tracked and, in particular, the relevance of Work Package 5 to the problem of rapid response catchments was highlighted.

- Liaison with the EPSRC Flood Risk Management Research Consortium (FRMRC) programme has been maintained and input was made to planning of the NERC Flood Risk from Extreme Events (FREE) programme.

- Links were maintained with related EA/Defra FFW (Flood Forecasting and Warning) programme projects, particularly the Storm Scale Modelling project, which completed in early 2005, and the follow-on Extreme Event Modelling project, both carried out by the Met Office.

- The European Commission FLOODsite programme provides Europe-wide collaboration in flood forecasting and warning activities.

4 Achievements of the Project

The achievements of the Extreme Event Recognition Project Phase 2 are summarised below in work package order.

Extend the historical analysis of extreme events to more recent and less extreme events.

This work was carried out by W. Hand of the Met Office.

A method of selecting a sample of ‘less extreme’ point rainfall cases occurring in the UK during the 20th Century was identified. Using this method, 210 Less Extreme events were identified: 54 were frontal cases, 104 were convective and 52 orographic. Whilst doing the selection an additional 10 Extreme events (5 frontal and 5 orographic) were found bringing the total number to 60. Random samples of 35 convective, 15 frontal and 10 orographic cases were drawn from the Less Extreme set for deeper analysis and for comparison with the Extreme events. Statistical analyses of differences between the two sets were undertaken. The main conclusions of these parts of the study were as follows:

- *Differences between the monthly distributions of Extreme and Less Extreme events are small* with the Less Extreme sample having a slightly more even spread throughout the year peaking in July as opposed to June in the Extreme sample.

- *There is a significant link between the number of Extreme events in a decade and the decadal North Atlantic Oscillation index measured between Gibraltar and Iceland.* The implication is that the frequency of Extreme point rainfall events might have a relationship to changes in global weather patterns.

- *A frontal rainfall event has a greater probability of being Extreme as opposed to Less Extreme the closer it is to a low centre.* The speed of a depression and bearing of a location from the low centre cannot be used in isolation to distinguish an Extreme from a Less Extreme frontal event. However, an Extreme event is very unlikely from a depression passing to the north of a location.

- *Orographic situations that lead to Extreme orographic rainfall are significantly different to those that give Less Extreme values.* In all the Extreme cases winds at 600m above ground had a trajectory between 210 and 250 degrees with a long fetch across the Atlantic at speeds greater than 15 m s^{-1} from a sub-tropical origin with dew points greater than 14ºC. 60% of Less Extreme cases had conditions differing in some aspect from those prevailing in the Extreme cases.

- Convective events are complicated. *The main conclusion is that Extreme convective events last significantly longer on average than Less Extreme ones.* However, there are also some other differences. Less Extreme events tend to have higher CAPE (Convective Available Potential Energy: a measure of the atmospheric energy available for release by convection) on average than Extreme events. Less Extreme convective events lasting longer than one hour require less moisture near and above ground than those lasting less than that. They also require less moisture than all Extreme events. Extreme events lasting less than one hour require more moisture than those with a longer duration. The implication of all this is that Extreme convective events can be put into two categories;
    1. *Convective point rainfall events lasting less than an hour usually triggering in a very moist atmosphere with convective clouds forming rapidly (e.g. Carlton-in-Cleveland, Wisbech)..*
    2. *Convective point rainfall events lasting longer than one hour that do not necessarily require a very moist atmosphere nor high values of CAPE but do require an environment that will permit repeated generation of convective cells in the same place (e.g. Boscastle, Hampstead and Halifax storms).*

- In Phase 1 it was concluded that the presence of large hail (stones > 15mm diameter) was an important indicator that a convective event could become Extreme. However, large hail have been found to occur in the Less Extreme cases and differences in the number of occurrences between the two sets are insignificant. *So the presence of large hail by itself is not an indicator that a convective situation will become extreme.*

- A general conclusion is that *an Extreme convective point rainfall event will occur either through the efficient and rapid conversion of a moisture-rich atmosphere into heavy rainfall or by repeated generation of deep convective cells in the same area. The latter scenario would have a variety of causes often due to complicated interactions within and between the atmosphere and ground (e.g. Boscastle).* An implication of this is that the parameters presented in Phase 1, deemed to be important for Extreme convective rainfall, are far too simple and insufficient to distinguish an Extreme fall from a Less Extreme fall.

- By comparing all Extreme with all Less Extreme point rainfall events it has been demonstrated that the underlying causal meteorological conditions are part of a continuum. There seems to be no sudden “jump” from one condition to another that would cause an event to become Extreme. Many factors usually have to come together to provide the ingredients for an Extreme point rainfall.

Five extreme point rainfall events occurring in the 21st Century were identified. All of them fitted into the framework of Phase 1 results and were consistent with the conclusions noted above.

Develop and evaluate an extreme event prediction system based on indicators identified in Phase 1.

This work was carried out by W. Hand of the Met Office, with input from T. Wood, I. Pearse and A. Pickles of the Environment Agency, and from many flood forecasters in the Environment Agency SW, NW and Thames regional offices.

The characteristics identified in Phase 1 were turned into algorithms and coded into the Bayesian prediction scheme as described in the final report of the work package, included as Annex 2 of this report.

A user requirement for the trial was specified with T. Wood (SW Region), I. Pearse (NW Region) and A. Pickles of the EA and signed off by the Project Board in September 2004 in time for the Trial to begin at the end of October and then run continuously for one year to November 2005. Three EA Regions were involved: NW England, SW England and Thames. This choice maximised the chances of getting a variety of weather types over a year to thoroughly test the system. Trial outputs were sent by automated e-mail to EA Regional officers and no operational EA staff were involved. This was to avoid confusion and the potential for conflict with operational forecasts. Met Office forecasters at Exeter, Manchester and London also had access to Trial outputs so that they could comment (if they wished) on potential usefulness.

The full specification and results of the trial are documented in the trial report attached as Annex 2. The key results were:

- A successful trial was completed, despite only one Extreme rainfall event occurring during the period (Carlisle flooding, 7 January 2005). Met Office forecasters thought that trying to forecast for Catchments was very ambitious and that the Area (County) scale would have been more appropriate. The Met Office Manchester forecasters were disappointed with the Carlisle case saying that the predicted probabilities could not distinguish that event from others forecast during the Trial with similar probabilities. However, they praised the useful guidance from the MM on that day, which alerted them to the possibility of heavy rainfall (but not Extreme rainfall).

- The Extreme rainfall forecast for Carlisle was a near-miss. The case clearly indicated the potential usefulness of orographic predictors provided that their location was accurate and that actual rainfall was entirely orographic. If the orographic enhancement predictors had been over the Lake District then the Mesoscale Model forecast of very heavy rainfall would have been supplemented by a high probability that an Extreme fall could occur.

- The objective verification gave a weak signal that the Trial performed best in Frontal & Orographic (FO) cases giving a larger spread of forecast probabilities. However, the FO case studies showed that the predictors led to an over-prediction of the probability of extreme rainfall based on actual rainfall observed in the Trial Regions and radar imagery. This was a common feature in the FO cases. (*Note that Carlisle was not an FO case*).

However, all the FO cases subjectively classified as a poor fit to the Phase 1 conceptual model correctly gave low (<10%) forecast probabilities of Extreme rainfall. This indicated some skill in the ability of the predictors to spot a potential severe event.

- Mesoscale model rainfall accumulation forecasts were demonstrably very good at the Catchment scale when maximum model rainfall accumulations in a Catchment were verified against maximum radar rainfall accumulations. However, in the FO cases there was a clear signal for significant over-prediction of amounts when durations exceeded 12 hours, for example the 27 July 2005 case.

- The objective and subjective assessments of Trial performance in convective cases showed that Extreme rainfall probabilities (albeit low) were predicted too frequently and over too large an area. For example, in the Boscastle case, Extreme rainfall was predicted at 10-15% probability in many parts of southern England. The inclusion of a crude stationarity predictor from the CDP (Convection Diagnosis Procedure) was not successful and it is clear that the Trial probabilities were picking out areas of potentially heavy convective rainfall as opposed to Extreme rainfall. The predictors used in the Trial were unable to adequately distinguish areas of potentially Extreme convective rainfall from the rest.

- The objective verifications lead to the tentative conclusion that employing the techniques used in the Trial forecast probabilities above 10% would at least indicate a potential for some very heavy rainfall. However, it is thought that that threshold would likely change with a different set of predictors or methodology.

- The Bayesian probability system required some ingenuity in setting prior and inverse probabilities and the corruption of the file containing climatological probabilities of predictors during the Trial led to absurd probabilities being output. This indicated sensitivity of the overall system to the priors, inverse and climatological probabilities. There is also still an issue with independence of predictors and it is not clear that the procedure adopted in the Trial was the best way to combine information from combinations of predictors.

- The derivation of predictors and their probability of exceeding important threshold values was satisfactory but could be improved. The method chosen in the Trial made best use of available operational outputs. However, several assumptions were made, for example, in determining airmass source dewpoint for the orographic predictors. The large scale predictors also suffered from the relatively coarse resolution of the ECMWF global model ensemble data

Evaluate a vorticity indicator for extreme events.

This work was carried out by Prof. C. Collier at Salford University, with input from P. Clark and S. Ballard at the Met Office, Joint Centre for Mesoscale Meteorology, Reading University.

The study demonstrated that unless model output is available with a resolution of around 1 km or better then the proposed vorticity indicator does not provide any useful information relating to extreme precipitation events.

Drawing upon related work on the assimilation of radar data into the variational analysis scheme of the Met Office Unified Model, it was demonstrated that this approach offers considerable potential to improve forecasts of wind and rain.

It is clear that high resolution numerical weather forecasts will have error characteristics that vary between different types of events. Using another area of related work, stochastic approaches to dealing with the error characteristics in hydrological models were demonstrated.

Develop spatio-temporal rainfall datasets using radar and raingauge data from historical heavy rainfall events, enhanced to represent extreme events, and use them to evaluate the extreme event performance of hydrological models.

This work was carried out by R.J. Moore, S.J. Cole, V.A. Bell and D.A. Jones at CEH (Wallingford).

One orographic, one frontal and four convective rainfall events with radar coverage were selected along with three extreme flood case studies, one for each type of rainfall. Hydrometric data for these were obtained and are included in the Extremes Dataset that forms an important output of this study (see Annex 4b).

The PDM (Probability Distributed Model) was chosen as representative of a lumped rainfall-runoff model and is in use operationally by the Agency. The Grid-to-Grid model, developed by CEH to exploit spatial information in gridded rainfall data and topographic datasets, was used as the distributed model.

Different spatial rainfall estimators based on radar and/or raingauge data were formulated for use with lumped and distributed hydrological models. A multiquadric surface fitting technique was developed that creates a raingauge-only rainfall surface by forming gridded estimates of rainfall from the point raingauge values. This technique was also used to combine raingauge and radar data to create a raingauge-adjusted radar estimate of rainfall. The gridded rainfall estimators were suitable for use as input to the distributed model. They could also be viewed through Hyrad allowing catchment average rainfall, needed for lumped modelling, to be calculated.

From a hydrological perspective, an appropriate test of a rainfall estimator is its ability to predict simulated river flow through a rainfall-runoff model. Conclusions about the rainfall estimators from a hydrological perspective are given below.

- Generally raingauge-only based estimators gave the best rainfall-runoff model performance for both models over the extreme events of interest and the periods used for calibration.

- Radar rainfall estimators, without raingauge-adjustment, produced model hydrographs that intermittently over-/under-estimated observed flows. The Nimrod QC (Quality Controlled) product gave better model performance than the raw radar product but was still not as good as the raingauge-only simulations.

- Adjusting radar data using raingauge data (at 15 minute time intervals) dramatically improved model performance to a level comparable with raingauge-only rainfall estimators. This highlighted the added value that combining raingauge and radar data can have for hydrological modelling whilst preserving the spatial information contained in the radar data.

- However, radar data unadjusted by raingauge data can still be used as a complementary form of rainfall estimate, having particular advantages in areas with relatively few raingauges and for observing convective storms that are not always sampled by the raingauge network.

For each extreme flood case study both rainfall-runoff models (PDM and Grid-to-Grid) were calibrated using each of the three rainfall estimators (radar, raingauge-only and raingauge-adjusted radar). The calibrated models were then assessed over the extreme flood event of interest and any failings noted. This prompted development of a prototype distributed model that utilises soil/geology datasets in addition to topography. The calibrated PDM input files have been included in the Extremes Dataset.

For each case study both rainfall-runoff models (PDM and Grid-to-Grid) were calibrated using each of the three rainfall estimators (radar, raingauge-only and raingauge-adjusted radar) over periods that excluded the extreme events. These calibrated models were then assessed over the calibration and extreme events and any failings noted. The findings of this assessment are summarised below.

- Model performance was best for the simply responding upland catchments where topographic controls dominate hydrograph formation and soil/geology/land-cover controls are homogeneous or weak. Lowland basins having strong heterogeneous soil/geology controls proved more challenging to model. The lumped PDM model almost always offered a marginal improvement over the Grid-to-Grid model, at least at the gauged sites used in model calibration.

- Over the case study extreme events the two models were generally in close agreement and both tended to underestimate the observed flood peak.