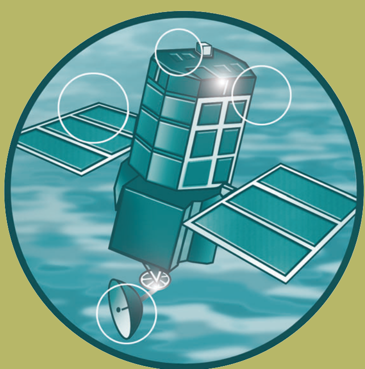
Joint Defra/EA Flood and Coastal Erosion
Risk Management R&D Programme

Extreme Event Recognition
Phase 2

R&D Technical Report FD2208/TR



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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.

CONTENTS

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:-

- o Picking out threatening orographic events using the criteria in the Phase 1 Report.
- o Identifying slow moving frontal zones (particularly warm occlusions or warm fronts) with high precipitation rates and the presence or not of embedded instability.
- o Identifying regions lying close to (within 200 km, say) and to the north and west of the centre of a slow moving depression.
- o 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.
- o 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.

Again, best performance was achieved for the upland catchments. The performance of the area-wide Grid-to-Grid model for the extreme orographic event affecting the River Kent was particularly noteworthy as it successfully predicted the flow across five gauged sites. This has obvious implications for providing flood warning of extreme events at any location within the region, whether gauged or ungauged.

- The relatively poor model performance for the extreme frontal event affecting the Upper Thames and Stour lowland catchments reflects the difficulties encountered during model calibration. This has been attributed to strong heterogeneous soil/geology controls on flood response and prompted development of a prototype distributed model able to make use of spatial soil/geology property datasets.

- It is difficult to attribute the general model underestimation of the observed flow peaks to any one cause. The flow observations, derived from extrapolated rating curves, provide a major source of uncertainty as the flood peaks were the largest on record at all gauging stations and were generally out-of-bank. The Environment Agency's Best Practice Guidance Manual W6-061/M on extension of rating curves at gauging stations provides guidance on how this issue may be investigated further.

- Understanding the flood genesis over a wide area for the Easter 1998 widespread frontal storm over the Upper Thames and Stour is important for identifying possible flood-prone areas. Strong heterogeneous soil/geology controls on flood response, not represented in the simple Grid-to-Grid model formulation, motivated the prototyping of a formulation that uses soil/geology datasets. The prototype model shows encouraging partial success in achieving a consistent area-wide simulation using a single parameter set.

A credible and practical approach to transforming historical spatial rainfall fields to create more extreme rainfall datasets was developed. A Rainfall Transformation Tool with 4D visualisation was created that can change the position, movement, orientation, size and shape of a spatio-temporal rainfall dataset. The historical and artificial storms and their flood response were assigned return periods, using methods developed from the Flood Estimation Handbook (FEH), serving to place their severity in context.

Over 100 amplified storms were constructed using the above methodology and are contained in the Extremes Dataset (Annex 4b). This allowed the flood response experiments to investigate complex storm-to-catchment interactions and to give improved understanding of extreme flood genesis. The simulations using both models (lumped and distributed) have given insights into their individual merits and limitations. Key outcomes of these flood response experiments are summarised below.

- *Long duration (>15 hours) frontal and orographic events*
  For amplified widespread frontal or orographic rainfall events the lumped and distributed models were expected to agree well. There was good agreement between models for all case studies except the Sor which served

to illustrate how models that agree well during historical events can diverge when using amplified storms. This type of model failure is usually due to one model being inadequate in some way (e.g. a missing process or a breakdown of a process under extreme conditions) or the inappropriate selection of one or more model parameters. For the Sor, the Grid-to- Grid model wave speed parameters need to be increased to avoid unrealistic land surface storage of water and therefore it was the model calibration that failed rather than the model. Identifying why models diverge under amplified extreme storms is vital for understanding extreme flood genesis and improving the physical-conceptual development of models and their robustness under extreme rainfall.

The experiments revealed that for quickly responding catchments the rainfall intensity profile over short durations (less than a day) is the principal factor determining flood magnitude whilst for slowly responding catchments the long duration rainfall total is the principle factor.

- *Convective events*
  For a given case study catchment, the flood response of lumped models for short duration events is dominated by the storm total and not the spatio-temporal storm pattern. A consequence is that all short duration storms cause lumped models to produce similarly shaped hydrographs.

  In contrast the Grid-to-Grid model proved to be very sensitive to the spatio-temporal pattern of the amplified extreme storms due to the topographic routing and runoff controls used. In particular storm location, spatial extent, spatial intensities and direction and speed of travel significantly affected the distributed model simulation resulting in more plausible flood responses. This emphasises the potential benefit of using distributed models when exposed to extreme and/or unusual convective storms. This has obvious repercussions when interfacing hydrological models to ensemble rainfall forecasts, particularly if convective storms are predicted.

- *Extreme event recognition*
  The flood response experiments have shown that exposing distributed hydrological models to storm conditions greater than those in the historical record can identify locations within a catchment that may be particularly vulnerable to flooding. This provides support to extreme flood recognition in advance of one occurring. Flood mitigation measures can be planned and flood warning schemes instigated. An awareness of the context within which extreme floods may develop will help in flood preparedness.

During the historical event analysis and flood response experiments, obvious model failure has been noted as and when it occurred and where possible, a cause attributed. Possible causes of model failure include: poor coding of the model, inappropriate selection of model parameter values, model configuration, missing physical processes in the model and/or model limitations. Appendix D of the Work Package report at Annex 4a demonstrates how a poorly formulated model solution can lead to chaotic disturbances in flow values at fixed time-points when using fixed duration rainfall profiles of changing magnitude. This model failed when subjected to unrealistically high values of rainfall input in excess of 15 metres in 12 hours. Therefore, it is better to destruction test models by subjecting them to realistic extreme rainfalls (e.g. use FEH derived return periods as a guide) rather than using unrealistic values to force model failure.

A major output of the study is the ‘Extremes Dataset’ and its accompanying documentation (Annex 4b). The collated raingauge, radar, river flow/level and MORECS potential evaporation data and created spatial rainfall estimates (historical and amplified) has generated a unique extreme storm dataset. Hyrad can be used to view the spatio-temporal rainfall data and, with the help of supplementary software, to relocate and scale (in magnitude) any of the historical or amplified storms.

- The ‘Extremes Dataset’ provides an excellent platform for hydrological model testing and development and should be used to its full potential. The inclusion of data used for calibration purposes increases the value of the dataset, allowing users to recreate the entire process of model calibration through to model evaluation over the extreme storm events.

- It also provides a valuable test-bed for developing distributed model initialisation and state-updating procedures (for use in real-time flood forecasting) using observational data at several spatial locations.

- The software developed for users to transpose and scale storms, along with the ‘Extremes Dataset’ documentation (Annex 4b), makes the dataset even more flexible and useful. For example, flood warning practitioners within the EA can run ‘what if?’ scenarios using realistic extreme storms over any target catchment and study the hydrological model responses.

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

This work was carried out by M. Dale, J. Dent and P. Dempsey at the Met Office with input from numerous flood forecasting and warning practitioners in the Environment Agency regional offices.

The objective of this work package was to establish the user requirements for a decision support tool to assist Environment Agency Flood Forecasting and Warning staff to identify catchments at risk of flooding during ‘extreme’ (distinct from ‘severe’) events. The work is related to but independent from other work packages.

The work comprised two consultation phases in which a series of interviews with Environment Agency staff was conducted to assess users’ requirements for a decision-support tool in relation to current flood forecasting and warning practice. The proposed tool was based on the scoring methodology originally proposed by Professor Collier in Phase 1 which comprised a set of fixed risk flood risk criteria, antecedent conditions, and dynamic meteorological variables. The list was expanded in Phase 2 to include a number of additional variables and a weighting system, after consultation with the EA. A proposed format for a decision-support tool was put forward in an Analysis Report as part of this work package in September 2004.

Results of the consultation analysis are summarised in the four following paragraphs:

- A detailed analysis of historic storm events carried out in Phase 1 went some way towards identifying the conditions likely to generate extreme flood events, and proposed a methodology to identify the relative susceptibility of catchments to flooding under extreme conditions. Phase 2 has built on the work of Phase 1 by introducing the concept to the EA users and proposing aspects to develop of a tool to suit specific requirements. The findings of the two consultation phases have indicated a requirement for a tool to assess catchment flood susceptibility though stopping short of a real-time decision-support tool for all regions.

- Whilst there was a positive response by consultees to the proposal for enhanced tools for alerting duty officers to the most severe impacts of extreme rainfall, there was concern that the benefits of the DST (Decision Support Tool) were insufficiently demonstrated. The overall impression was that there was insufficient support by users for the tool as proposed and insufficient justification for further research to develop the decision support methodology. Outputs from the other work packages in this project may be better at addressing immediate expectations for real-time extreme event predictions that can be incorporated into existing modelling systems.

- There was some concern that extreme events should be treated separately from ‘ordinary’ severe events, warnings of which are currently covered by the Environment Agency’s four stage flood warning procedures. The EA has been keen to point out that any new tool or technology should fit with current forecast products and should not add complexity to the monitoring requirements of FFW (Flood Forecasting & Warning) staff. The proposed DST format is to be independent of current forecast products including Nimrod short-range quantitative precipitation forecasts, the 5-day weather forecast, and heavy rainfall and severe weather warnings. However, new products, including probabilistic forecasts, could be incorporated into an operational DST at a later stage if required.

- Further work would be required to develop the risk assessment approach to confirm or refute that some catchments are more susceptible than others. This would require compilation of a detailed database of all UK catchments including detailed assessments of flood risk and catchment and water-course characteristics. Much of this work will have already been done by the Environment Agency for regional catchment plans and flood asset management plans. In the short-term it is a suggested that the assessment of particular flood susceptibility is carried out for a group of pilot catchments to demonstrate the methodology.

5 Principal Conclusions

The principal overall conclusions resulting from the Extreme Event Recognition Project 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.

More detailed conclusions are presented below in work package order.

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

- 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 if the low centre is to the south and close to the location.
  - Extreme convective events are distinguished from less extreme ones primarily by the length of the rainfall event.

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

- The predictors identified in Phase 1 do not provide an adequate basis for identifying 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.

Evaluate a vorticity indicator for extreme events

- The proposed vorticity indicator does not provide useful information relating to extreme precipitation events except at model grid lengths of 1km or better, which currently are not available in operational numerical weather prediction models – but may be in the future.

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

- Storm data of convective, orographic and frontal type were obtained for historical cases and modified in location, scale, magnitude and movement using a Rainfall Transformation Tool, so as to provide flexible datasets with which to test and evaluate hydrological models. It was found that quality-controlled radar data needed to be first combined with raingauge observations to be useful for flood modelling purposes.

- Use of the spatio-temporal rainfall datasets was demonstrated using examples of lumped and distributed hydrological models. The results revealed possible shortcomings in the model assumptions and improved formulations investigated where appropriate.

- An extension to the project resulted in the data sets being made available to the Environment Agency in a form compatible with their operational systems. Training was provided to practitioners to demonstrate how the datasets could be used to evaluate and test flood forecasting models in their ability to assimilate extreme rainfall.

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

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

- There was a need to clearly distinguish between normal flood events and extreme events

6 Recommendations for future work

The following overall recommendations are made on the basis of the work as a whole:

- 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 early forecasts of extreme events.

The following detailed recommendations for future work are made in relation to the work streams undertaken in this project. At the time of writing of this final report there are no fixed plans to progress this work although it is anticipated that elements will be identified in future Defra, Environment Agency and Met Office research and development programmes either jointly or individually.

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

- Given the significant but modest differences in underlying meteorological conditions between Less Extreme and Extreme point rainfall events, it is clear that the processes that must come together to trigger an Extreme event are still not fully understood. It is important; therefore, that Extreme and Less Extreme cases should be studied and compared in detail using high resolution NWP models that can best represent the non-linear processes that occur in these systems. Since most Extreme point rainfall events are convective, and that type is the least understood, then effort should be concentrated on those cases.

- This study has briefly looked at possible links of Extreme event frequency with global climate indicators. It could be fruitful to explore the tentative link found with the North Atlantic Oscillation index (NAO) further and also consider the possibility of further linkages, for example with hurricane frequency and intensity.

- 21st Century Less Extreme rainfall events should be identified and the database of Extreme and Less Extreme rainfall events should be maintained. It is recommended that this should be done in the Met Office.

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

- Consider developing a prototype “heads-up 24 hours ahead” probabilistic Extreme rainfall warning system for EA Areas for frontal/orographic events. Use recently developed Met Office high resolution ensembles and high resolution Mesoscale model to develop and provide improved predictors, utilising results from work package 1.

- Use the frequently updated and high resolution model post-processing suite (now being developed in the Met Office) to monitor all evolving weather situations (especially convective) from an Extreme rainfall point of view and consider developing and providing frequent short-term forecasts of the probability of Extreme rainfall in EA Catchments (0-6 hours ahead) and EA Areas (0-24 hours ahead).

- Both the EA and Met Office forecasters should be fully involved in any initiative and it is recommended that at least one of the above activities be undertaken given the potentially catastrophic consequences of Extreme rainfall falling without warning and the firm foundation of work and experience provided by this Trial.

Evaluate a vorticity indicator for extreme events

- It is recommended that further work be undertaken to investigate the impact of the assimilation of radar reflectivity, humidity information derived from radar (refractivity) and radial winds into high resolution configurations of the Met Office Unified NWP Model.

- If this direction is to lead to improved forecasts of extreme events then stochastic hydrological modelling approaches will need to be investigated further to ensure that the error characteristics of numerical rainfall forecasts are dealt with appropriately.

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

Rainfall estimators

- A good spatial rainfall estimator for rainfall-runoff modelling is provided by the ‘zero parameter’ raingauge-only multiquadric surface. This gridded rainfall estimator could be implemented nationwide, or on a catchment/regional basis, using existing functionality within Hyrad. A raingauge-based spatial rainfall estimator is seen as essential if distributed grid-to-grid modelling is to be used by the Agency. Further investigation might focus on the performance for sparse raingauge networks and what implications the ‘flatness at large distance’ constraint may have at locations far from dense parts of the network.

- Raingauge-adjustment of radar, at a 15-minute interval, provided much improved rainfall-runoff model performance relative to unadjusted radar data. The adjustment should be implemented operationally and could use existing Hyrad functionality.

- In the context of flood forecasting, the raingauge-adjusted radar rainfall (adjusted at intervals of 15 minutes) might be considered for use in nowcasting of rainfall, including use within Nimrod and Hyrad.

Hydrological model development

- The simple Grid-to-Grid formulation performed well for catchments dominated by topographic controls and is recommended for operational trials in upland catchments. The model should add value when forecasting the area-wide flood response, at gauged and ungauged locations, from extreme and/or unusual storms.

- Hydrological distributed models of a conceptual-physical type should be developed further to capitalise on spatial soil/geology/land-cover datasets. Such approaches are key to forecasting the area-wide flood response of complex catchments with strong heterogeneous soil/geology controls and for identifying particularly flood-prone locations. Further development and operational trials of the prototype distributed model are recommended.

- The application of distributed area-wide models for operational flood warning could be improved by addressing the following challenges: model initialisation, forecast updating, uncertainty estimation and utilisation of future advances in ensemble rainfall forecasting.

The Extremes Dataset

The Extremes Dataset and the software developed to allow users to transpose and scale storms (in magnitude) should be used:

- to destruction-test models and model calibrations within realistic rainfall ranges (e.g. use FEH for guidance)

- to serve as a catalyst for model improvement
- to run flood forecast 'what if?' scenarios using realistic extreme storms over any target catchment(s) of interest
- to train flood forecasters and flood warning officers by gaining the experience of extreme storms and the associated flood responses
- to gain a greater understanding of flood genesis
- to identify locations vulnerable to extreme floods, even in advance of them occurring – methods for implementation need to be developed.

Rating curve extension

- The extreme event case studies should be used to explore the feasibility of rating curve extension via physically-based methods, such as those outlined in the Agency's Best Practice Guidance Manual W6-061/M.

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

- Undertake pilot flood susceptibility mapping studies for a number of catchments in all EA regions which support the initiative. Each pilot study should include catchments of varying characteristics (area, mean channel length and slope, soil moisture deficit, etc.) and should make use of the time-to-peak maps produced by Jeremy Benn Associates. Detailed information on known flood risk (such as structures, populations at risk) would be collected from participating Environment Agency Regions. The flood susceptibility maps should then be tested with historic extreme rainfall event information to assess their usefulness as a decision-support tool for flood warning duty officers. It is recommended that, if successful, the method should be extended across England and Wales.
- Carry out a demonstration of a 'real-time' version of the flood susceptibility assessment tool. This would be a GIS-based application for use in combining GIS-based flood risk maps with meteorological forecasts and observations dynamically in real-time. The outputs from work package 2 and other packages (especially work package 2 probabilistic forecasts) could also be assessed with a view to incorporating them into a dynamic flood susceptibility tool to indicate the composite level of flood risk.
- It is recommended that the proposed Decision Support Tool forms the basis for assessing the areas at risk within the planned Flash Flood Register.

7 References

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Appendix A Detailed aims of the project

The detailed aims of the Extreme Event Recognition Project Phase 2 are presented below in work package (WP) order.

WP 1 Extend the historical analysis of extreme events to more recent and less extreme events.

The aim was to extend the Phase 1 analysis to consider more recent and less severe storms, 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. The following specific activities were planned:

- Select an appropriate threshold for less severe events, and randomly select 50 cases within this range of return periods from the Met Office catalogue of heavy rainfall events.
- Analyse the cases by extraction and interpretation of data from British Rainfall and published Daily Weather Reports, specifically noting differences from the extreme events analysed in Phase 1.
- Apply the quantitative algorithms developed under WP2 to these events.
- Repeat the analysis for any storms since 1999 that exceed the 1:100 year threshold defined in Phase 1.
- Analyse the results to determine the extent to which the extreme events can be considered to be a distinct population from the less extreme ones, using both qualitative and quantitative approaches.
- Report the case studies and analysis results in an update to the Phase 1 Report, to be delivered in November 2005 (attached as Annex 1 of this report).

WP 2 Develop and evaluate an extreme event prediction system based on indicators identified in Phase 1.

Our approach is to develop and evaluate a probabilistic extreme event forecast product 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 forecast variables.

- Prepare a detailed specification of the product to be trialled and how it will be evaluated, in consultation with Met Office service providers and forecasters, and with Environment Agency practitioners. The specification will document *inter alia* the content and format of the product, including spatial and temporal extent and resolution; how a service would be delivered and who would use it; the input data sources to be used; the length and organisation of the trial, including a technical specification of how it will run; and the verification scores that will be computed to assess its performance. (Met Office with advice from Salford)

- Develop software to generate quantitative measures of each Phase 1 indicator (orographic exposure, fetch, geostrophic wind speed, airmass source dewpoint, speed of depression, frontal type, position and movement, CAPE, presence of large hail, multicell organisation, mesoscale triggering) from fields of basic mesoscale model data. Compute statistics of the relationship of each algorithm to the occurrence of extreme events using historical data from Phase 1. (Met Office with advice from Salford)

- Develop software to generate probabilistic predictors for extreme rainfall events of convective, frontal or orographic type, using a Bayesian approach. The prior probability will be defined using statistics of the relationship between mesoscale model predicted rainfall amounts and extreme observed rainfall, based on historical verification. The contribution of the individual indicators will be computed from the statistics obtained in the previous step. (Met Office)

- Develop software to generate the required products from the probabilistic predictors, to make them available in agreed formats, and to verify their performance. (Met Office)

- Set up and run an end-to-end trial, incorporating improvements that are identified from experience of its performance or from work under work packages 1 and 3. (Met Office)

- Document system for users, write reports and scientific paper. Submit paper to Defra conference. (Met Office)

WP 3 Evaluate a vorticity indicator for extreme events.

Work carried out at the University of Salford on the identification of extreme convective events based on an analysis of vorticity (Sleigh and Collier, 2004). The basis of the proposed technique is the recognition of developing symmetry, and then asymmetry, in the field of the tipping term in the vorticity equation. It was planned to examine model output data and data from the Chilbolton S-band Doppler radar system and, possibly, the new Southeast C-band radar system, to test the validity of this proposal. In the event, data from the Thurnham radar were not available in time to be used.

- Identify test cases for which Doppler data (Chilbolton and the new Southeast radar, if available) and mesoscale model data are available and assemble the required data (Salford & Met Office)

- For one selected case, run a finer resolution version of the mesoscale model that is expected to come into operational use in 2005, and extract the required data for analysis. (Met Office)

- Develop and implement code to calculate the diagnostics. (Salford)

- Evaluate performance of the technique on the selected case studies for each of the data sources.

- If deemed worthwhile, add this predictor to the real-time trial (WP 2) using just mesoscale model data. (Met Office with advice from Salford)

- Assess results from the trial, prepare report and submit scientific paper. (The report on the results is attached as Annex 3 of this report.)

WP 4 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.

We propose a study using two rainfall-runoff models in operational use, along with a spatially-distributed model formulation able to take full advantage of spatial weather radar data. Since models in use by the Agency share common elements, it will be possible to comment more broadly on the implications for other models.

- To ensure full engagement with the Environment Agency as the primary beneficiary of the research, a Consultative Stage at Project Inception will aim to confirm the requirements of the Agency, the methodology to be adopted and the format of the results. It is proposed to use two operational lumped and one grid-based distributed rainfall-runoff models. An Inception Report will be produced.

- Select 5 extreme events (including the Walshaw Dean storm) that are sufficiently recent to include radar data coverage, and which generated floods in catchments for which historical flow records are available. The extreme storms and associated catchments will be chosen to encompass the main classes of extreme event identified in Phase1: convective, frontal and orographic. The catchments will ideally have gauging stations with good rating curves for high flows but, where necessary, rating extension will be undertaken. Assemble the data required, including radar data from the Met Office or CEH (requiring one month's radar data per case to support rainfall-runoff model water store accounting); raingauge data from the EA or Met Office, and PE data from the EA. Perform an initial analysis on the data.

- Calibrate the selected models for the required catchments and carry out a detailed examination of catchment model behaviour - encompassing consideration of storm movement, storm coverage and soil moisture condition. We would aim to seek ways of improving the model formulations where deficiencies become apparent.

- Develop and agree with the Environment Agency a credible and practical approach to creating extreme rainfall scenario datasets, through amplification of the historical data, taking into account areal extent and frequency issues and the information contained in Appendix A of the Phase 1 Report. The dataset will be trialled on two operational rainfall-runoff models as a demonstration of their use by the Agency. Guidance on the estimation of extended flood flow ratings for assessing the impact of extreme rainfall events and to allow forecasting systems to handle them will be given.

- Prepare a report including guidelines and recommendations for rainfall-runoff modelling under extreme storm conditions. Submit the scientific results to an international refereed journal. Submit a paper for presentation at the Defra conference.

WP 5 Establish a User Requirement for a decision support tool in the light of Phase 1 recommendations and current practice in the Environment Agency.

The approach involves two separate stages of consultation with the practitioner (the flood forecasting and warning staff of the EA) before a standard decision-support methodology is proposed. This activity will make full use of the close relationship that has been established between Met Office and Environment Agency hydrologists, assisted by use of ex EA staff to undertake the work. It is recognised that a possible outcome is that there is insufficient commonality in the components for aiding decision making across the country and that regional intelligence tables may be superior to a nationwide facility.

- We will gather the existing intelligence tables, or any catchment-specific decision making information that has been documented by flood forecasting and warning teams, to examine the nature of this information and any commonality across the regions. This will require the contractor to meet with EA flood forecasting and warning teams to gather this information and note down any specific uses of this information to the region concerned. During these meetings views and ideas will be sought from practitioners on their perceived requirement for a decision-support tool that may provide
    (i) An indication of a fixed measure of a catchment/river reach/flood warning area susceptibility to flooding,
    (ii) The impact of flooding within the catchment incorporating factors such as the at-risk population and the capability of response organisations to respond (e.g. is the at-risk community remote?)

(iii) An indication of the potential flooding severity within a catchment based on the susceptibility and the rainfall/storm characteristics forecast or expected.

(iv) A spatial distribution of risk that would incorporate all of the above.

This consultation will aim to explore the need for such a tool amongst practitioners, clarify the elements that are considered most important, assess whether current intelligence tables used by practitioners can be incorporated into the decision tool and evaluate the priority that such work should be given.

- Results of the consultation will be subjected to a desk study evaluation of the catchment-specific decision-making information to determine the extent of cross-region similarities.

- The findings of the desk study of collated EA information used in intelligence tables or decision making information will be viewed in context with the scoring system components identified in Phase 1 (stationarity of rain, soil moisture deficit, etc.) and additional parameters that are considered essential to adequately assess risk, if appropriate. From this analysis the identification of suitable components to make up a cross-regional (England & Wales) decision-support tool would be made. It may be found that there are many or only a few components which are applicable for decision-support across England & Wales.

- The final stage will be to return these findings to the flood forecasting and warning teams in the EA for their comment. The comments received will then be used as approval (or otherwise) of cross-regional (and cross-catchment) components that can be used in a decision-support tool across England & Wales. From this, a specification will be proposed that identifies the need for the work, scopes out the elements of the work and outlines an appropriate approach to be taken forward in Phase 3.

Appendix B Project Board Membership

Brian Golding	Met Office	Chair, Consortium Leader
Linda Aucott	Defra	Project Manager
Tim Wood	EA, SW region	User
Ian Pearse	EA, NW region	User
Alison Pickles	EA, HQ	User
Chris Collier	Salford University	Research Team Leader
Bob Moore	CEH (Wallingford)	Research Team Leader
Tim Harrison	EA, NW region	User
Helen Stanley	EA	User

Appendix C Glossary

CAPE	Convective Available Potential Energy: a measure of the energy available to drive convection
CDP	Convection Diagnosis Procedure: diagnoses parameters - such as cloud top, peak rain rate and duration - from the thermodynamic structure of the atmosphere
DST	Decision Support Tool: a software tool that carries out a flood risk analysis based on catchment characteristics and forecast precipitation
EA	Environment Agency
ECMWF	European Centre for Medium Range Weather Forecasts, based in Reading, UK
EPSRC	Engineering & Physical Sciences Research Council
FEH	Flood Estimation Handbook
FFW	Flood Forecasting and Warning
FO	Frontal and Orographic: classes of extreme rainfall events
FREE	Flood Risk from Extreme Events: a NERC research programme
FRMRC	Flood Risk Management Research Consortium: an EPSRC research programme
GIS	Geographical Information System: a software tool
MM	Mesoscale Model: the Met Office regional NWP model covering the UK
MORECS	Met Office Rainfall & Evaporation Calculation System
NAO	North Atlantic Oscillation: a periodic change in the intensity of the westerly winds over the North Atlantic
NERC	Natural Environment Research Council
NWP	Numerical weather prediction: a computer-based weather forecasting methodology
PDM	Probability Distributed Model: A hydrological modelling technique
PMP	Probable Maximum Precipitation
SMD	Soil Moisture Deficit: a measure of the ability of the soil to absorb moisture
STEPS	Short Term Ensemble Prediction System: a probabilistic precipitation nowcasting technique
WP	Work Package

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