Weather radar and hydrology: a UK operational perspective

ROBERT J. MOORE, STEVEN J. COLE & ALICE J. ROBSON
Centre for Ecology & Hydrology, Wallingford OX10 8BB, UK
rm@ceh.ac.uk

Abstract Weather radar forms an essential and integral tool for water management in the UK, especially for monitoring and warning of flooding: the main focus of this perspective paper. An overview is first given of the radar network and its associated rainfall data products used by the environment agencies responsible for flood defence. The Hyrad (HYdrological RADar) system is deployed to receive, visualise and analyse these products, and to further process them for use within flood forecasting systems. Regional systems employ networks of models configured to make forecasts at specific locations. Very recently, countrywide systems employing an area-wide G2G (Grid-to-Grid) hydrological model have been implemented. Both types of system, used operationally in a complementary way, are reviewed in relation to their use of, and demands for, weather radar-related data. Activity on implementing probabilistic approaches to flood forecasting which benefit from using radar in ensemble rainfall prediction is outlined, and future prospects discussed.

Key words weather radar; hydrology; rainfall; flood; forecasting; distributed hydrological model

USE OF RADAR IN REGIONAL FLOOD FORECASTING SYSTEMS

Weather radar forms a key tool for water management across the UK, especially in support of flood warning, on account of its timely data availability and detailed spatial coverage. Quality-controlled rain-rates are available as "observation data" every 5 min on a 1 km grid formed as a composite from a network of 18 C-band radars over the British Isles (Harrison *et al.*, 2012). The rain-rate fields are used in forming "forecast data" as deterministic nowcasts of rainfall out to 6 h: fields are advected using an optical flow algorithm and merged with numerical weather prediction (NWP) rainfalls according to their relative accuracy at different lead-times (Bowler *et al.*, 2006). Rainfall accumulations for 15-min intervals that account for storm movement are available, both as observation and forecast data, for use with rainfall–runoff models for flood forecasting in real-time.

These gridded rainfall products are disseminated by the Met Office to environment agencies in England and Wales, and Scotland, who employ the Centre for Ecology & Hydrology's Hyrad system for real-time data receipt, processing, archiving and display (Moore *et al.*, 2004). The CatAvg component of Hyrad is configured to calculate catchment average time-series from the observed and forecast radar rainfall products (and NWP rainfalls for longer lead-times) for onward transmission to the National Flood Forecasting System (NFFS) for England and Wales and to "FEWS Scotland", both based on the Delft-FEWS open system architecture (Werner *et al.*, 2009). The NFFS is implemented as a set of regional flood forecasting systems which make flood forecasts at specific locations in support of flood warning for each region, and using configurations of models representing the river network (FEWS Scotland is configured to warning scheme areas). A variety of model types are used, including rainfall–runoff, transfer function, snowmelt, hydrological routing, and hydrodynamic routing (Moore *et al.*, 2005). Forecast updating methods employ observed river flows available at the time of forecast construction to improve accuracy. The radar rainfall forecasts out to 6 h are critical for making extended lead-time forecasts, beyond the lag time of the catchment for a given forecast location. For longer forecast lead-times of a day or more, use is made of the NWP rainfalls. In the future, these predictions will increasingly benefit from radar data assimilation when initialising the weather model (Ballard *et al.*, 2012).

The utility of radar is judged to be less when observation-based rainfall estimates are required to maintain the water balance of rainfall–runoff models of catchments. This applies both for offline hydrological model calibration and in real-time up to the time the forecast is made. Experience has shown that raingauge data, although providing only point estimates of rainfall at gauge locations, can provide a more robust estimator than radar, which can suffer from transient errors (Cole & Moore, 2008). Even when radar rainfall is used in combination with raingauge network data through a merging procedure, these errors can prove pervasive and suppressed only to a limited degree. As a consequence, it is common that the preferred rainfall estimator for use with rainfall–runoff models is based on raingauge data at times when observational data are available. However, availability of raingauge data in real-time is constrained by the polling regime of the telemetry schemes, which in the UK predominantly employ PSTN technology: charging tariffs (and sometimes battery life) can inhibit routine frequent polling.

Radar rainfall data do not suffer from such availability issues, and therefore are configured to be used as the default for times when limited or no polled raingauge data are available. The greater utility of raingauge network data over use of radar rainfall data of course depends on circumstance: the relative sparsity of a raingauge network to the small scale of convective storms is a common argument forwarded in support of weather radar for areal rainfall estimation. There are over 900 raingauges providing 15-min rain accumulations available to NFFS over England and Wales, and more than 250 for the system used over Scotland, with areas of about 151 000 and 79 000 km^2, respectively but gauge density is very varied.

USE OF RADAR FOR COUNTRYWIDE FLOOD FORECASTING

The regional flood forecasting systems are primarily configured to make flood forecasts at river gauging station locations, and their station flow records are used for model calibration. Forecasts of river flow for ungauged locations are required in these regional systems, for example where lateral inflows are input to hydrological channel flow routing models and hydrodynamic river models. The methods used vary from simple scaling of flows from nearby gauged locations (based on area and possibly rainfall climatology for the catchment) through to simple methods of rainfall–runoff model transfer from gauged sites. The latter approach can benefit from radar through using forecast rainfalls over the ungauged lateral inflow area.

A comprehensive study of methods of flood forecasting for ungauged locations (Moore *et al.*, 2006, 2007) recognised shortcomings in conventional methods: it argued the case for pursuing a distributed grid-based hydrological modelling approach. This allows a storm pattern to be shaped into a flood over space and time using information on properties of the terrain, soil/geology and land cover to configure the distributed model, allowing flows to be forecast everywhere in a physical-conceptual way. In particular, there is no need to work with aggregated “catchment characteristics” in this approach but to deal directly with landscape properties at the grid-scale of the model. A 1 km grid coincident with the radar grid is judged appropriate for current flood forecasting requirements, with soil and land-cover gridded datasets also available at this resolution.

A special kind of distributed hydrological model was conceived for flood forecasting application that differed from conventional physics-based distributed models that employ detailed representation of soil water movement in the vertical, and are typically not well supported by available soil information. This physical-conceptual distributed model, called the Grid-to-Grid or G2G Model, is of depth-integrated form and suitable for use with national datasets of terrain/soil/geology/land-cover properties along with dynamic gridded rainfalls derived from radar and raingauge observations and weather models.

The G2G was prepared and trialled for operational use within NFFS under the R&D project “Hydrological Modelling using Convective Scale Rainfall Modelling” (Environment Agency, 2009), with particular emphasis on its use for probabilistic flood forecasting using high resolution ensemble rainfall forecasts from STEPS and forms of NWP product. During the course of the project “The Pitt Review” of the Summer 2007 floods (Cabinet Office, 2008) recognised the need for a consistent countrywide approach to flood forecasting capable of providing forecasts “everywhere” out to 5 days, and that the new distributed grid-based model could fulfil this need. Regional case studies of G2G over the southwest and Midlands were, as a consequence, extended in the final phase of the project to include a G2G configuration with England and Wales coverage for fluvial rivers. This was followed by an “Operational Implementation of G2G on NFFS” project which culminated in the G2G being used within the newly-formed joint Environment Agency and Met Office Flood Forecasting Centre when preparing the Flood Guidance Statement for England and Wales (Price *et al.*, 2012). The role of this national G2G model was seen as complementary to the more detailed NFFS regional models that are typically calibrated to make forecasts at specific gauged locations. Of particular importance is the coherent spatial picture of flooding and its evolution over time that the G2G can provide, not possible with the regional network models.

Much experience was gained in the use of radar rainfall data, in both observation and forecast form, through these G2G developments. National calibration of the G2G model exposed difficulties with the routine use of gridded rainfall estimators based on radar, either used alone or in combination with raingauges. Long-term average gridded radar rainfall maps exposed the usual problems of beam blockage and discontinuities when compositing data from different radars. Transient errors in radar rainfall were detected in the G2G river flow simulations, when compared with river gauging station records, and proved hard to diagnose and remove. Whilst tipping-bucket raingauge records from some 981 stations could be affected by anomalous single values, over-recording due to tip doubling or by missing values reported as zero, these proved easier to diagnose and account for in an automated way (Howard *et al.*, 2012). The outcome of these exploratory investigations was that national calibration of G2G was best achieved using a gridded raingauge-only rainfall estimator: it proved more robust and free of the transient radar rainfall errors that could seriously corrupt efforts at model calibration. The operational model configuration was similarly configured to employ, as first priority, the raingauge-only rainfall estimator in its hierarchy of sources (Price *et al.*, 2012), but would commonly default to a merged gauge-radar or radar-only estimator due to constrained real-time access to polled raingauge telemetry data.

The G2G was subsequently configured to Scotland to meet requirements of the newly formed Scottish Flood Forecasting Service, operated jointly by the Scottish Environment Protection Agency and Met Office. Whilst the poorer and more uneven coverage of raingauges over Scotland initially suggested radar rainfall would prove of greater value for G2G model calibration, the greater robustness of the raingauge records won through, as they did for England and Wales; as a result, a similar rainfall source hierarchy has been adopted for operational use. Cranston *et al.* (2012) provides further information on the use of weather radar and countrywide flood forecasting in Scotland, noting the significant step-change in warning capability the G2G facilitates: moving from a few flood warning schemes to complete coverage for fluvial rivers.

USE OF RADAR IN PROBABILISTIC FLOOD FORECASTING

At present, flood forecasting and warning practice in the UK is primarily deterministic in nature. Active steps are being taken to explore the benefits of probabilistic methods that take forecast uncertainty into account, especially those associated with the rainfall predictions used to extend the lead-time of flood forecasts. Progress is being made possible through the availability of STEPS, which in addition to a deterministic rainfall forecast out to 6 h (based on radar extrapolation merged with NWP rainfalls) can provide an ensemble of equally-likely forecasts. An initial demonstration of its use with the PDM catchment rainfall–runoff model was provided by Pierce *et al.* (2005).

Approaches for accounting for uncertainty in the NFFS regional model networks was addressed in the “Risk-based Probabilistic Fluvial Flood Forecasting for Integrated Catchment Models” R&D Project; an overview is provided by Laeger *et al.* (2010) whilst the pathway to operational implementation remains an open question and the subject of further investigation. Of particular relevance to weather radar is an approach that combines “model” uncertainty (embracing errors in the model state, structure and its observed inputs) with rainfall forecast uncertainty, and is able to utilise the STEPS forecast rainfall ensemble for the latter. Standard ARMA (AutoRegressive Moving Average) model theory applied to the flood model errors, using a log transform to approximate a normality assumption, allows model uncertainty limits to be calculated for different lead times using estimates of the ARMA parameters and the residual error variance. The further uncertainty associated with using the STEPS forecasts can be captured by producing spaghetti plots of the forecast hydrographs using each ensemble member as the rainfall forecast, along with the ARMA model error uncertainty limits. This can be further simplified to obtain forecasts of flow at different lead-times corresponding to a given quantile (percentage exceedance) value and the associated model uncertainty limits at this value. Figure 1 plots the flow values for a specified quantile and different forecast lead times bracketed by the model uncertainty, along with the observed flows. Comparing the graphs obtained for high (90%), medium (50%) and low (10%) quantiles allows the uncertainty introduced by the rainfall forecasts to be appreciated separately from the model uncertainty delineated by the grey-shaded bands. Here, the PDM rainfall–runoff model is employed as the flood model for the Calder catchment to Todmorden and a 9-h (padded out to 20 h with zero rainfall) STEPS ensemble rainfall forecast is used with a time-origin at 06:00 h 21 January 2008.

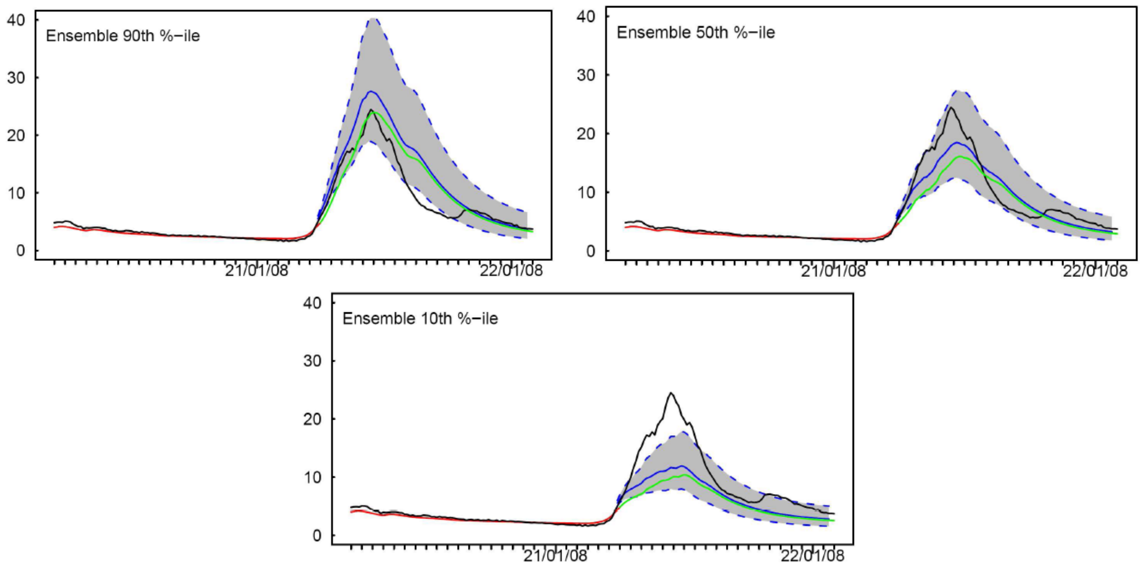

Fig. 1 Flood forecast uncertainty due to (i) model error: grey bands indicate 95% probability envelope, and to (ii) rainfall forecast error: indicated across the graphs by the high, medium and low (90, 50 and 100) percentile flows, calculated from the PDM rainfall–runoff model ensemble flow forecasts with STEPS forecast rainfalls (time origin 06:00 h 21 January 2008) as input. The percentile flows are green for simulated and blue for ARMA-updated forecasts. Observed and simulated flows are black and red lines, respectively.

An important purpose of the "Hydrological Modelling using Convective Scale Rainfall Modelling" R&D Project was to explore the use of probabilistic flood forecasting using ensemble rainfall forecasts, from STEPS and from future high-resolution NWP ensemble rainfall forecasts under development within the Met Office. It was recognised that the distributed nature of the G2G Model was particularly appropriate for use with rainfall forecast ensembles on account of its sensitivity to storm position, a major source of uncertainty in convective storms. Figure 2 shows the evolution of forecast maps of flood risk, here portraying the probability of exceeding the 10-year flood flow over the course of a flood event affecting the Avon and Tame catchments in the English Midlands. G2G is employing a STEPS ensemble rainfall forecast made at 09:00 h 20 July 2007, with forecasts beyond 6 h padded out with zero rainfall so as to facilitate tracking the movement of water down the river network in the G2G model forecasts. It can be seen how the "hotspots" of flood risk move from headwater streams down to confluences and larger rivers over the duration of the flood. Whilst the probabilities await a thorough assessment, it is clear that this approach has real value as an indicator of relative risk in space and time that can guide flood preparedness. A future R&D Project will explore the use of G2G to provide a new capability for flood forecasting of rapidly responding catchments, employing a new Blended Ensemble rainfall forecast out to 24 h that blends a high-resolution (2.2km) NWP with STEPS radar rainfall and noise extrapolation.

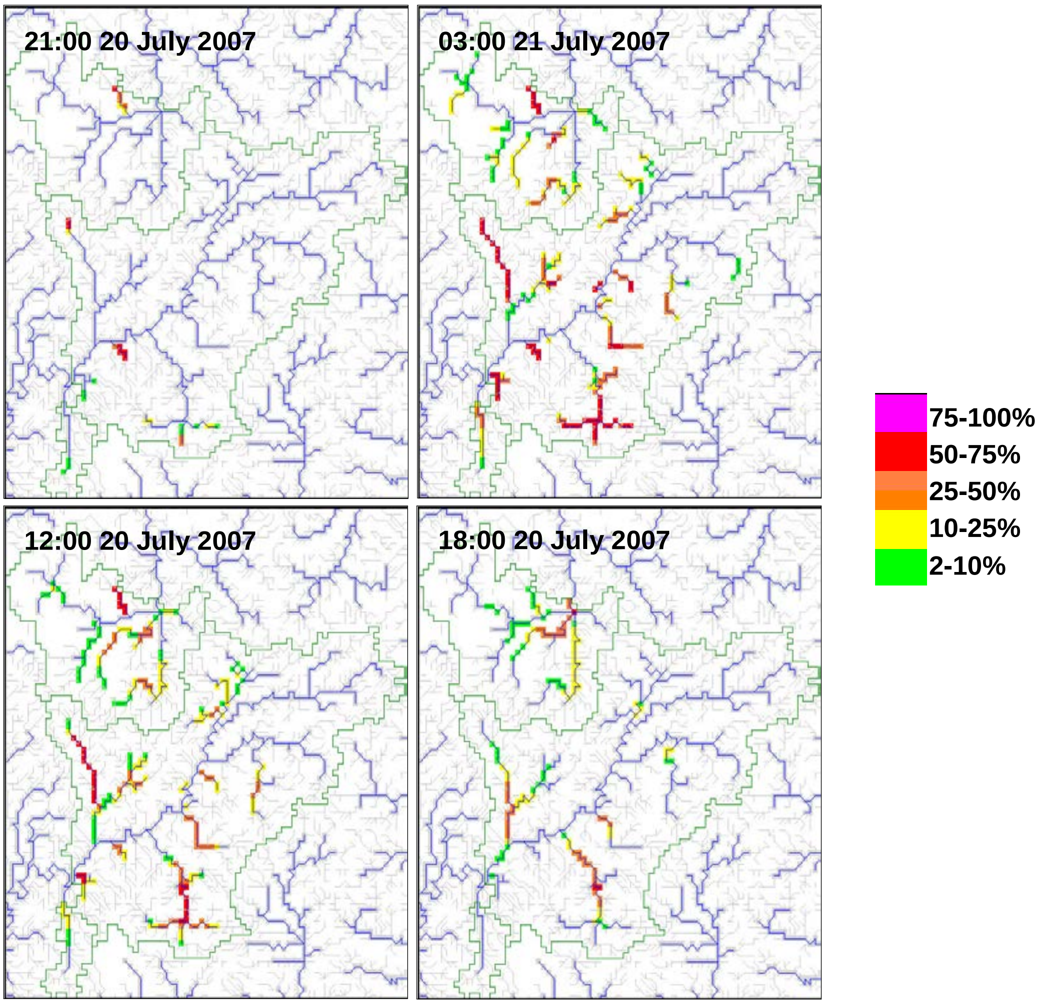

Fig. 2 Evolution of forecast flood risk for a summer 2007 flood event over the Avon and Tame catchments (English Midlands) obtained using the G2G Model and a STEPS ensemble rainfall forecast, showing progressive movement of "hotspots" from small headwater rivers to confluences and larger rivers. Bright (red and pink) colours indicate high probabilities (>50%) of exceeding the 10-year flood. Grey: 1 km river network; Blue: river network with drainage area >20 km^2; Green: boundary of modelled area.

FUTURE PROSPECTS

Whilst this perspective paper has focused on flood forecasting applications, there are other important developments in progress concerning the use of radar in operational water management. One area is the need to assess storm rarity in relation to monitoring urban drainage system compliance to decide whether storm water overflows are indicative of design exceedance or a result of system failure requiring mitigating action. A development of the Hyrad system will integrate the Flood Estimation Handbook assessment of rainfall rarity, using an intensity-duration-frequency method, with radar rainfall to produce map displays of rainfall rarity and integrated estimates for areas contributing runoff to urban drainage systems (Cole *et al.*, 2012).

The Pitt Review highlighted the importance of pluvial (surface water) flooding and the lack of a suitably tailored warning service. In response, an Early Rainfall Alert service has been developed based on rainfall rarity exceedance which makes use of radar rainfall data. A future opportunity is to explore the use of modelled surface runoff from the G2G distributed hydrological model: this not only accounts for rainfall intensity, but also the condition of the receiving ground in relation to its land-cover, soil/geology properties and changing wetness. Dynamic maps of surface water flood risk with reference to impacts might be developed as operational products guiding management decisions. A further opportunity concerns bathing water regulations and the need to give warning of potentially unsafe conditions. The area-wide coverage provided by both radar rainfall products and the G2G model offers the prospect of modelling the heterogeneous pollution response of differing source areas leading to improved bathing water quality forecasts in real-time. Modelling the combined morphological and flood responses to intense convective rainfall is an additional challenge that will benefit from the use of radar rainfall estimates.

An on-going renewal programme providing dual-polarisation capability to the UK radar network, and advanced processing procedures, aims to improve the quality of radar rainfall for hydrological use. An assessment is proposed aimed at ensuring the hydrological benefits are fully appreciated, exploited and pulled through to operational use.

REFERENCES

Ballard, S., Zhihong, L., Simonin, D., Buttery, H., Charlton-Perez, C., Gaussiat, N. & Hawkness-Smith, L. (2012) Use of radar data in NWP-based nowcasting in the Met Office. In: *Weather Radar and Hydrology* (ed. by R. J Moore, S. J. Cole & A. J. Illingworth) (Proc. Exeter Symp., April 2011), IAHS Publ. 351. IAHS Press, Wallingford, UK (this issue).

Bowler ,N.E., Pierce, C.E. & Seed, A.W. (2006) STEPS: A probabilistic precipitation forecasting scheme which merges an extrapolation nowcast with downscaled NWP. *Quart. J. Roy. Met. Soc.* 132(620), 2127–2155.

Cabinet Office (2008) The Pitt Review: Lessons learned from the 2007 floods. http://webarchive.nationalarchives.gov.uk/20100807034701/http://archive.cabinetoffice.gov.uk/pittreview/thepittreview/final_report.html.

Cole, S. J., McBennett, D., Black, K. B. & Moore, R. J. (2012) Use of weather radar by the water industry in Scotland. In: *Weather Radar and Hydrology* (ed. by R. J Moore, S. J. Cole & A. J. Illingworth) (Proc. Exeter Symp., April 2011), IAHS Publ. 351. IAHS Press, Wallingford, UK (this issue).

Cole, S. J. & Moore, R. J. (2008) Hydrological modelling using raingauge-and radar-based estimators of areal rainfall. *J. Hydrol.* 358(3–4), 159–181.

Cranston, M., Maxey, R., Tavendale, A., Buchanan, P., Motion, A., Cole, S., Robson, A., Moore, R. J. & Minett, A. (2012) Countrywide flood forecasting in Scotland: challenges for hydrometeorological model uncertainty and prediction. In: *Weather Radar and Hydrology* (ed. by R. J Moore, S. J. Cole & A. J. Illingworth) (Proc. Exeter Symp., April 2011), IAHS Publ. 351. IAHS Press, Wallingford, UK (this issue).

Environment Agency (2010) Hydrological modelling using convective scale rainfall modelling – phase 3. Project: SC060087/R3, Authors: J. Schellekens, A. R. J. Minett, P. Reggiani, A. H. Weerts (Deltares); R. J. Moore, S. J. Cole, A. J. Robson & V. A. Bell (CEH Wallingford). Research Contractor: Deltares and CEH Wallingford, Environment Agency, Bristol, UK, 231pp. http://nora.nerc.ac.uk/13829/.

Harrison, D. L., Norman, K., Pierce, C. & Gaussiat, N. (2012) Radar products for hydrological application in the UK. *Water Management* 165(2), 89–103.

Howard, P. J., Cole, S. J., Robson, A. J. & Moore. R. J. (2012) Raingauge quality-control algorithms and the potential benefits for radar-based hydrological modelling. In: *Weather Radar and Hydrology* (ed. by R. J Moore, S. J. Cole & A. J. Illingworth) (Proc. Exeter Symp., April 2011), IAHS Publ. 351. IAHS Press, Wallingford, UK (this issue).

Laeger, S., Cross, R., Sene, K., Weerts, A., Beven, K., Leedal, D., Moore, R. J., Vaughan, M., Harrison, T. & Whitlow, C. (2010) Probabilistic flood forecasting in England and Wales – can it give us what we crave? *BHS Third International Symposium*, Role of Hydrology in Managing Consequences of a Changing Global Environment, Newcastle University, UK, 19–23 July 2010, British Hydrological Society, 8pp.

Moore, R. J., Bell, V. A., Cole, S. J. & Jones, D. A. (2007) Rainfall–runoff and other modelling for ungauged/low-benefit locations. Science Report – SC030227/SR1, Research Contractor: CEH Wallingford, Environment Agency, Bristol, UK, 249pp. http://nora.nerc.ac.uk/1134/.

Moore, R. J., Bell, V. A. & Jones, D. A. (2005) Forecasting for flood warning. *C. R. Geosciences* 337(1–2), 203–217.

Moore, R. J., Cole, S. J., Bell, V. A. & Jones, D. A. (2006) Issues in flood forecasting: ungauged basins, extreme floods and uncertainty. In: *Frontiers in Flood Research* (ed. by I. Tchiguirinskaia, K. N. N. Thein & P. Hubert), 103–122, 8th Kovacs Colloquium, UNESCO, Paris, June/July 2006. IAHS Publ. 305. IAHS Press, Wallingford, UK.

Moore, R. J., Jones, A. E., Jones, D. A., Black, K. B. & Bell, V. A. (2004) Weather radar for flood forecasting: some UK experiences. *6th Int. Symp. on Hydrological Applications of Weather Radar*, 2-4 February 2004, Melbourne, Australia, 11pp.

Pierce, C., Bowler, N., Seed, A., Jones, A., Jones, D. & Moore, R. (2005) Use of a stochastic precipitation nowcast scheme for fluvial flood forecasting and warning. *Atmos. Sci. Letters* 6(1), 78–83.

Price, D., Hudson, K., Boyce, G., Schellekens, J., Moore, R.J., Clark, P., Harrison, T., Connolly, E. & Pilling, C. (2012) Operational use of a grid-based model for flood forecasting. *Water Management* 165(2), 65–77.

Werner, M., Cranston, M., Harrison, T., Whitfield, D. & Schellekens, J. (2009) Recent developments in operational flood forecasting in England, Wales and Scotland. *Met. Appl.* 16(1), 13–22.