(Proceedings of a symposium held in Exeter, UK, April 2011) (IAHS Publ. 351, 2012).

Representing the spatial variability of rainfall for input to the G2G distributed flood forecasting model: operational experience from the Flood Forecasting Centre

DAVID PRICE[1], CHARLIE PILLING[1], GAVIN ROBBINS[1], ANDY LANE[1], GRAEME BOYCE[1], KEITH FENWICK[1], ROBERT J. MOORE[2], JOANNE COLES[3], TIM HARRISON[3] & MARC VAN DIJK[4]

1 *Flood Forecasting Centre, Met Office, FitzRoy Road, Exeter, Devon EX1 3PB, UK*
david.a.price@environment-agency.gov.uk

2 *Centre for Ecology & Hydrology, Wallingford OX10 8BB, UK*

3 *Environment Agency, Horizon House, Deanery Road, Bristol BS1 5AH, UK*

4 *Deltares, Inland Water Systems, Deltares, Delft, The Netherlands*

Abstract Over the year 2010 the Flood Forecasting Centre (FFC) calibrated and implemented a distributed flood forecasting model to support the FFC's remit to provide flood risk forecasts across England and Wales, UK. The distributed nature of the model, designed to run at 15-min time-steps on a 1 km^2 grid, enables the spatial variability of rainfall measurements and forecasts, rather than lumped catchment averages, to be captured. Such a distributed model should therefore benefit greatly from the spatial and temporal resolution afforded by radar observations. Initial results have highlighted the importance of the quality of the gridded rainfall fields and in a number of cases erroneous radar rainfall data have been shown to contribute to poor model performance. It is suggested that gridded datasets of sufficient quality will be best provided by capturing the spatial variability inherent in radar data together with raingauge data in a merged product.

Key words flood forecasting; distributed flood forecasting model; Flood Forecasting Centre; radar; Grid-to-Grid model

INTRODUCTION

In April 2009 the Flood Forecasting Centre (FFC) was established as a joint venture between the Environment Agency and the Met Office as a direct response to the Pitt Review (Pitt, 2008). The FFC is uniquely placed to deliver some of the key technical and operational recommendations set out in the Pitt Review in England and Wales.

In this paper we describe the introduction of a grid-based flood forecasting model for England and Wales (UK) and describe the ways in which radar data are employed within the modelling system. The model is referred to as Grid-to-Grid (G2G). The use of a grid-based model allows the spatial nature of rainfall, as represented by radar data, to be captured in a way that is not possible using lumped hydrological catchment models, which have traditionally been used for flood forecasting in the UK. Thus, capturing the spatial nature of rainfall using the G2G offers a significant advantage over lumped models, but it also raises challenges. Examples are given that highlight a number of issues arising from using radar rainfall data as an input to the G2G model, raising the challenge for the provision of more reliable data for use in an operational environment.

This paper first introduces the G2G model and its environment. The ways in which radar rainfall data are used within the modelling system are then explored, first with regard to the rainfall input data hierarchy used to generate a complete time-series prior to each model run, and then in relation to short-term forecasts (nowcasts). The impact of erroneous rainfall input data on model output is considered and finally, the paper considers opportunities for future developments in relation to radar rainfall.

THE G2G MODEL AND IMPLEMENTATION AT THE FFC

Overview of the G2G Model

The G2G (Moore *et al.*, 2006; Bell *et al.*, 2009; Environment Agency, 2010) developed at the Centre for Ecology & Hydrology (CEH) is able to provide a forecast of river flow across England

and Wales at a high temporal and spatial resolution (down to 1 km^2). As such, it has the capacity to forecast "everywhere" and lends itself to large-scale applications, including at national level. Figure 1 presents a schematic of the G2G model.

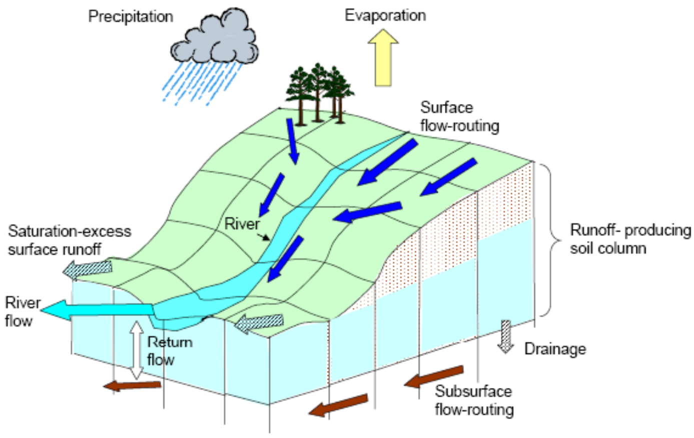

Fig. 1 Schematic of the G2G model.

The G2G is a physical-conceptual distributed, grid-based runoff production and routing model which contrasts with current hydrological model networks that generally comprise a connected set of catchment-based (lumped) rainfall–runoff models feeding into river routing reach models, providing forecasts at specific locations. Thus, the G2G employs a "grid-to-grid" formulation rather than the often used "source-to-sink" approach. It is designed to work with gridded rainfall estimates and can be used to forecast river flows at both gauged and ungauged sites.

The model has been calibrated using flow records from gauging stations on rivers throughout England and Wales. The model implemented at the FFC uses soil, geology and land cover spatial datasets, as well as terrain slope. This formulation makes explicit use of soil properties, including soil depth. These spatial datasets reduce the number of model parameters that require calibration.

Probability-distributed model theory is applied when representing surface runoff production. Water accounting principles applied to each grid square provides gridded surface and subsurface runoff for input to the G2G routing scheme. This scheme employs kinematic wave principles applied to channel and lateral inflows, and sub-surface runoff. The G2G is hosted on a platform based on Delft-FEWS (Werner *et al.*, 2004) and the forecasting system is referred to hereafter as the National Flood Forecasting System–Flood Forecasting Centre (NFFS–FFC).

Model input data: the data hierarchy

Prior to a G2G Model run, a complete time-series of gridded 15-min data at a 1 km^2 resolution must be generated for the entire domain of the G2G model. For precipitation, the following data sources are available to NFFS-FFC:

– Observed raingauge rainfall, from a network of 974 0.2-mm tipping-bucket raingauges across England and Wales.
– Observed radar rainfall rates, 1 km, 5 min resolution.
– Radar-based forecast rainfall accumulation, 2 km, 15-min time-steps out to 6 h – the STEPS (Short Term Ensemble Prediction System) control forecast – run every 15 minutes (96 forecasts per day).
– NWP forecast rainfall accumulation from the 4 km, NAE (North Atlantic and European, 12 km) and Global (25 km) Met Office Unified Models.
– Met Office Global and Regional Ensemble Prediction System (MOGREPS) ensemble forecast, 25 km, 24 members.

An integral part of this process requires HyradK (Moore *et al.*, 1994, 2005; Moore, 1999; Cole & Moore, 2009) to generate gridded rainfall data based on one of three options: raingauge-only, radar-only or raingauge-adjusted radar. These products are generated using a simple multiquadric surface-fitting technique.

Based on this set of available data, a hierarchy is used to prepare the gridded rainfall input to the G2G model (see Fig. 2). For the period up to the time of forecast, T0, the raingauge-only grid estimate from HyradK is the first data source, then the raingauge-adjusted radar from HyradK, and then the radar-only product. Operation rules are currently set for the raingauge-only option if up-to-date data are available from >75% of raingauges. The last-resort backup in this period, expected to be activated only rarely, is zero precipitation; note that for the last 2 h up to T0, radar-based forecasts or even NWP forecasts are used as a backup source in preference. For the first 6 h of the forecast the radar-based rainfall product (STEPS control forecast) will be used supplemented with (up to 36 h) the 4 km NWP product; this also serves as a backup for the radar-based forecast in the first 6 h of the forecast. For the longer lead-times, up to 5 days ahead, the 12 km NAE model and 25 km Global model products are used (12 km out to 54 h, then 25 km out to 5 days). If all fails, the zero precipitation backup option is used. A separate procedure is set up for the forecast using the MOGREPS ensemble product. In that case MOGREPS is the only source of precipitation in the forecast period (up to 54 h).

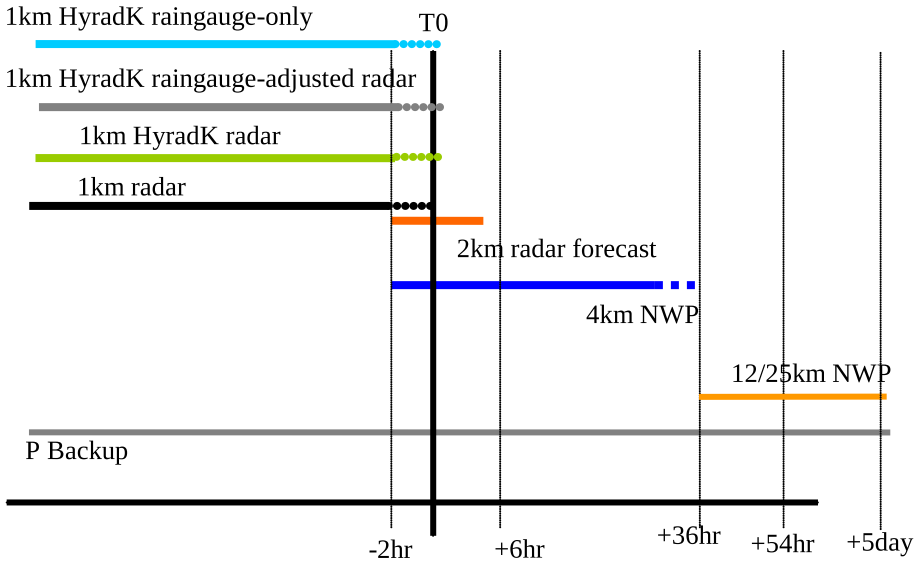

Fig. 2 Diagram showing the available precipitation sources relative to the time of forecast (T0) and their position in the precipitation data hierarchy (top line is first priority) that is applied when constructing input for the G2G.

SYSTEM EVALUATION

The G2G model is currently under a period of system evaluation within the FFC. As well as system and reliability performance, not considered here, particular attention was paid to the model's response to erroneous input data. As already stated, radar rainfall data coupled with the G2G enables the spatial nature of rainfall to be captured and exploited. However, the problems of erroneous radar rainfalls are exacerbated when operating at high spatial resolutions. During the period of system evaluation (since October 2010) the following examples highlighted the effects of such erroneous data.

Example 1 shows how clutter in radar data caused unusually high flows to be predicted at the Environment Agency's Manchester Racecourse flood warning site when little or no rainfall was actually observed or forecast (Fig. 3(a)). The radar observations, shown in Fig. 3(b), show an area of intense rainfall above the catchment feeding the Manchester Racecourse site. Investigation has shown these rainfall intensities not to be genuine, but due to radar clutter caused by Scout Moor wind farm. Clutter is an intermittent but common problem associated with radar rainfall and radar-based rainfall forecasts.

Example 2 shows how a radar spike from High Moorsley Radar (Fig. 4(a)) has resulted in G2G grid squares showing high return period flows where there are no actual river channels (Fig. 4(b)).

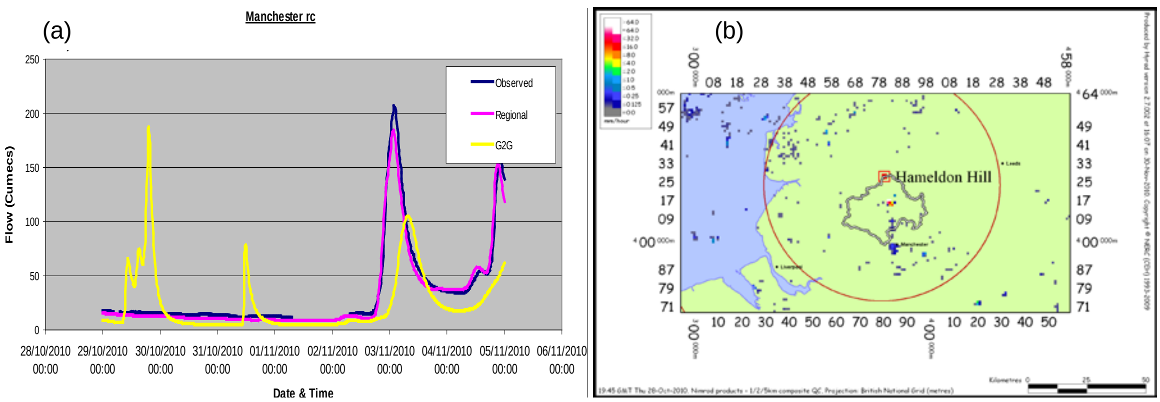

Fig. 3 (a) G2G and Regional model simulations of river flow and observations for Manchester Racecourse (the Regional model assumes knowledge of measured flows upstream) (b) radar actual showing anomalous echoes over the Manchester Racecourse catchment (both courtesy of Lindsay Ness, Environment Agency North West Region).

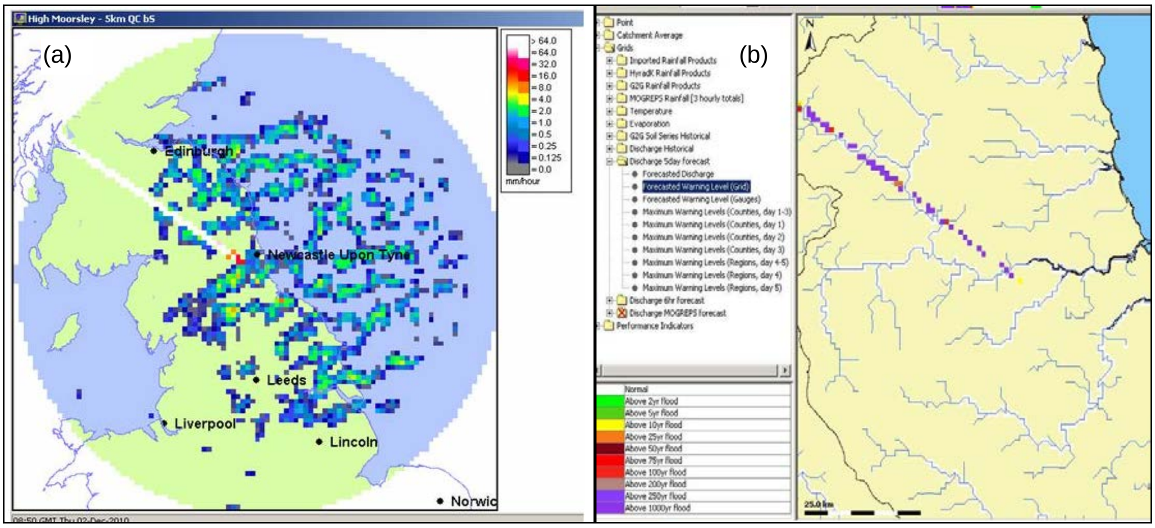

Fig. 4 (a) A radar spike in High Moorsley radar, 2 December 2010, (b) Grid-to-Grid output showing unrealistically high flow predictions away from river channels as a result of a radar spike.

Example 3 shows a test case where HyradK was used to produce raingauge-only and raingauge-adjusted radar estimates of 1-km gridded rainfall (the radar data product used was the UK 1/2/5 km radar composite) to simulate likely G2G performance during the notable Cumbria floods of 2009. Figure 5 maps the 1-km gridded rainfalls accumulated over a 3-day period obtained using three rainfall estimators: HyradK raingauge-only, UK 1/2/5 km radar and HyradK raingauge-adjusted radar. The underestimation of rainfall over Cumbria by the weather radar when compared to the interpolated raingauge image is apparent from an inspection of these maps.

Figure 6 shows the resulting G2G and observed hydrographs for the Cocker and Derwent catchments, which experienced some of the most severe flooding during this event. During this period it is clear that the hydrograph generated using the raingauge-only input compares best to the observations. The raingauge-adjusted radar data also provides a good match although the unadjusted radar data underestimates significantly. These results are consistent with those of Cole & Moore (2009), where further discussion can be found.

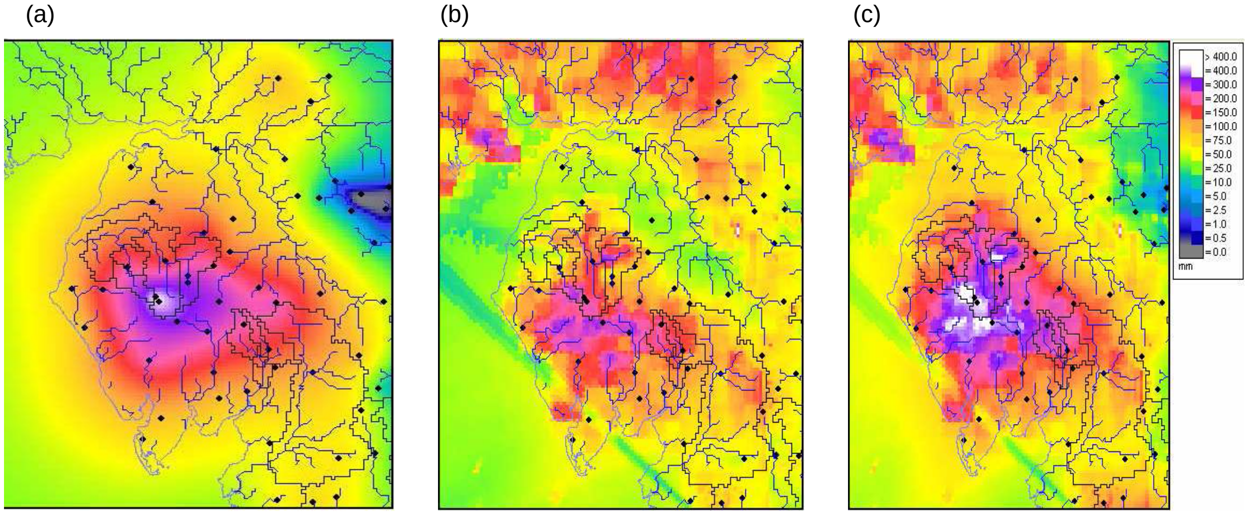

Fig. 5 Map of rainfall accumulations (mm) over Cumbria for the 3-day period ending 09:00 h 20 November 2009 obtained using the following rainfall estimators: (a) HyradK raingauge-only, (b) UK 1/2/5 km radar, and (c) HyradK raingauge-adjusted radar; dots indicate raingauges.

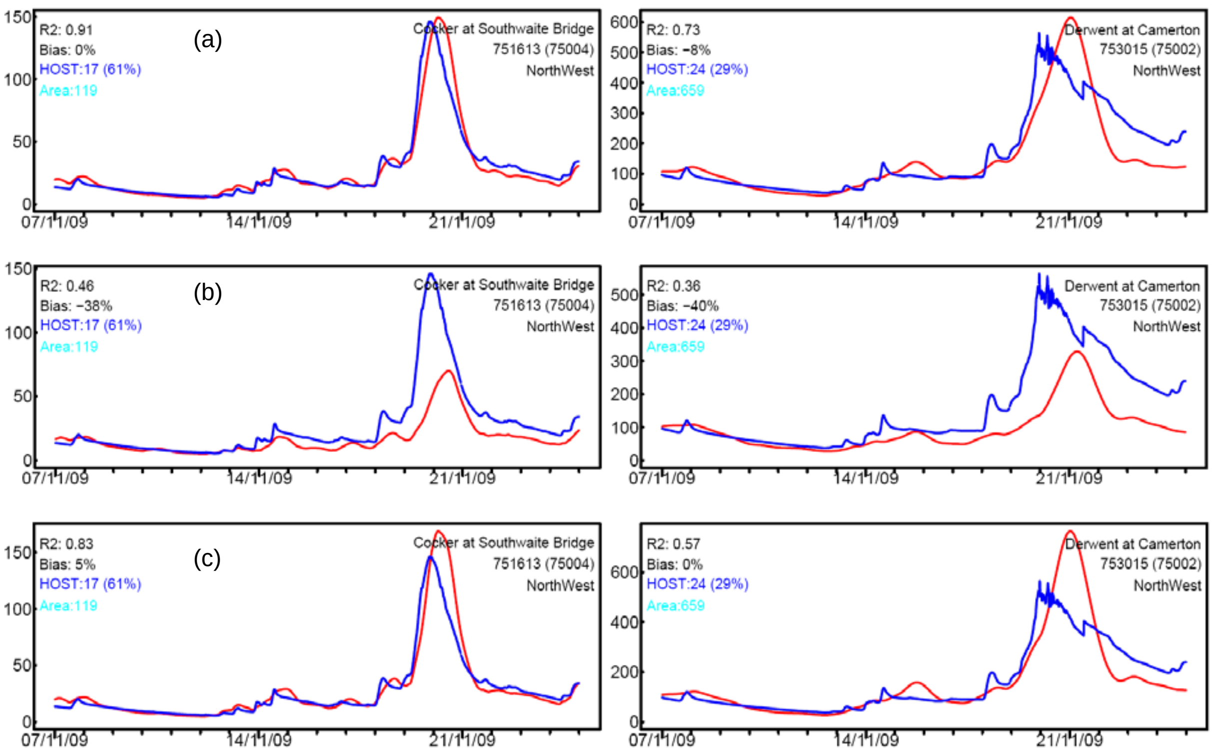

Fig. 6 Simulated hydrographs obtained using the G2G Model for catchments in Cumbria affected by the November 2009 floods. (a) HyradK raingauge-only rainfall, (b) Unadjusted radar rainfall and (c) HyradK raingauge-adjusted radar rainfall. Blue: observed flow; red: simulated flow.

DISCUSSION

For the benefits of a distributed modelling approach to flood forecasting to be fully realised the input data needs to accurately reflect the spatial variability of the rainfall. Such data are uniquely available from the UK radar network which has full coverage for England and Wales, with varying resolution, at a 5-minute interval. The examples given here show that these radar rainfall data are not always of a sufficient standard: with incidences of clutter, spurious radar spikes and radar under-estimating rainfall at the ground, resulting in poor model performance. Poor or erroneous radar rainfall data will impact on operational flood forecasting since radar data are used both in the data hierarchy invoked to generate a complete gridded rainfall time-series for the G2G model and as a basis for producing nowcasts, through the use of STEPS.

In a way that a lumped catchment approach may not, the G2G challenges the consistent quality of the radar rainfall data. As shown in the examples above, small areas of anomalous radar rainfalls can clearly adversely affect subsequent G2G forecasts presented at a 1 km scale, the effects of which would not be so clearly highlighted within forecasts from lumped catchment models. The requirement for good high-resolution rainfall accumulations, reflecting the spatial variability that only radar can provide, will continue as we are challenged to test our capability to forecast for rapidly responding catchments that can be of the order of 25 km^2 or smaller. It is evident that to generate accurate flood forecasts from a distributed hydrological model, such as G2G, requires a reliable and complete time-series of gridded precipitation data which must capture the spatial and temporal variability in observed rainfall. For real-time forecasting, timeliness is as important as capturing spatial and temporal variability and therefore radar still provides the best source for complete and timely rainfall accumulations over England and Wales. It is proposed that a reliable and accurate merged rainfall dataset – incorporating the strengths of both raingauge and radar sources – will play a critical role in meeting future challenges, including the provision of forecasts for rapidly responding catchments.

REFERENCES

Bell, V. A., Kay, A. L., Jones, R. G., Moore, R. J. & Reynard, N. S. (2009). Use of soil data in a grid-based hydrological model to estimate spatial variation in changing flood risk across the UK. *J. Hydrol.* 377, 335–350.

Cole, S. J. & Moore, R. J. (2009) Distributed hydrological modelling using weather radar in gauged and ungauged basins. *Adv. Water Resour.* 32, 1107–1120.

Environment Agency (2010) *Hydrological Modelling using Convective Scale Rainfall Modelling.* Science Report – SC060087. 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). Environment Agency, Bristol, UK, 240 pp.

Moore, R. J. (1999) Real-time flood forecasting systems: Perspectives and prospects. In: *Floods and Landslides: Integrated Risk Assessment* (ed. by R. Casale & C. Margottini), Chapter 11, 147–189. Springer.

Moore, R. .J., May, B. C., Jones, D. A. & Black, K. B. (1994) Local calibration of weather radar over London. In: *Advances in Radar Hydrology* (ed. by M. E. Almeida-Teixeira, R. Fantechi, R. Moore & V. M. Silva) (Proc. Int. Workshop, Lisbon, Portugal, 11–13 November 1991), Report EUR 14334 EN, European Commission, 186–195.

Moore, R. J., Jones, D. A., Black, K. B., Austin, R. M., Carrington, D. S., Tinnion, M. & Akhondi, A. (1994) RFFS and HYRAD: Integrated systems for rainfall and river flow forecasting in real-time and their application in Yorkshire. In: *Analytical Techniques for the Development and Operations Planning of Water Resource and Supply Systems.* BHS National Meeting, University of Newcastle, 16 November, BHS Occasional Paper no. 4, 12 pp.

Moore, R. J., Bell, V. A. & Jones, D. A. (2005) Forecasting for flood warning. *C. R. Geoscience* 337, 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), (8th Kovacs Colloquium, UNESCO, Paris, June/July 2006), 103–122. IAHS Publ. 305. IAHS Press, Wallingford, UK.

Pitt, M. (2008) Learning lessons from the 2007 floods. An independent review by Sir Michael Pitt. Cabinet Office, London, UK http://webarchive.nationalarchives.gov.uk/20100807034701/http://archive.cabinetoffice.gov.uk/pittreview/thepittreview/final_report.html.

Werner, M., van Dijk, M. & Schellekens, J. (2004) DELFT-FEWS: an open shell flood forecasting system. In: *Proc. 6th Int. Conf. on Hydroinformatics* (World 10 Scientific Publishing Company), 1205–1212.