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Integrating meteorological and uncertainty information in flood forecasting: the FLOODRELIEF project

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Abstract Flood forecasting specialists and operational water managers require ready access to a wide range of information, such as catchment status and meteorological forecasts, to make decisions during a flood. To have real value, however, decision-makers are now recognising that real-time flood management decisions must be based on an understanding of the uncertainties and associated risks. It is therefore critical for effective flood management to provide reliable estimates of the flood forecast uncertainty. To address these requirements the EU project FLOODRELIEF has focused on developing new ensemble-based methodologies for estimating and reducing forecast uncertainty and on the development of the FLOODRELIEF DSS, able to use ensemble methodologies to provide uncertainty information. This paper presents firstly, the development of a high-resolution mesoscale ensemble Quantitative Precipitation Forecast (QPF) system. An ensemble weather forecast is not only able to provide improvements in the forecast lead time and useful information about the nature of the weather system, but also estimates of the levels of confidence for the forecast. Investigations of the rainfall forecast uncertainty using this system and their impact on flood forecasts are presented for case studies in the UK. Secondly, to improve flood forecast accuracy using real-time data, as well as determining the propagation of uncertainty through the hydrological system, an ensemble Kalman filter methodology for data assimilation has been developed. An evaluation of the benefit of data assimilation in terms of forecasting accuracy is carried out and the performance of two different assimilation strategies is compared for case studies in the USA and New Zealand. Finally, a decision support system is presented that provides flood management and forecast information in a flexible, efficient and easily understood manner to operational users and decision-makers. A general framework for ensemble forecasting has been developed to provide a flexible approach for estimating uncertainty within this system. In this manner a direct and intuitive estimate of forecast uncertainties, that can be communicated to flood managers and decision-makers, is achieved.

Key words flood forecasting; precipitation forecasting; risk; uncertainty; data assimilation; downscaling; ensemble modelling; decision making

INTRODUCTION

Real-time flood forecasting systems that link weather forecasts and hydrological models with real-time measurements of the state of the river catchment, river discharges and water levels, can be used to respond to floods as they occur and to reduce their cost in terms of lives, property and the breakdown of infrastructure. In comparison to structural measures such as the construction of dams and polders or increasing bank levels, flood forecasting is cost effective and the environmental impacts are minimal. More importantly, when used for flood warning, these systems can save lives even in the most extreme events, whereas structural measures can only protect up to a finite level of flood risk.

Finally, flood forecasting is used by decision makers to take the most effective decisions for flood mitigation during a flood. A crucial aspect of such decision-making, which has only received limited attention in operational systems to date, is the need to understand and account for the uncertainty inherent in forecasting within the decision-making process. In an evaluation of the limitations of current forecasting systems, the FLOODRELIEF end users identified uncertainty as one of the most significant limitations in current forecasting systems (Butts *et al.*, 2005; Cadman *et al.*, 2007). In a recent survey of current practice, it was found that there was a general lack of understanding of the potential benefits of the operational use of forecasting uncertainty to improve the reliability of decisions (Todini *et al.*, 2006). A particular challenge for operational flood forecasting systems not found in other applications is that a rapid assessment of forecasting uncertainty is needed during a flood event.

Uncertainties are an inherent aspect of the flood forecasting process and there are a number of challenges in treating these uncertainties:

1. Quantification of the uncertainty sources.
2. Evaluation of the impact of the different sources on the flood forecast accuracy and uncertainty including their propagation from rainfall to river levels.
3. Reducing uncertainties using, for example, data assimilation, effective model calibration, ensemble modelling, etc.
4. Evaluation of the impact of the uncertainty on the decision-making and management options.
5. Provision of this uncertainty information in a manner that can be understood by operational forecasts and decision makers.

One of the main objectives of the EU project FLOODRELIEF was to attempt to address number of these challenges by developing appropriate methodologies and evaluating these in flood forecasting applications in a number of different catchments. FLOODRELIEF was undertaken by a group of eight partners, seven in Europe and one in China, with complementary expertise covering development and application of numerical weather forecasting systems, flood forecasting systems, weather radar, data assimilation, uncertainty estimation, flood warning and decision support tools.

A detailed description of the FLOODRELIEF projects, the partners, the project results and publications can be found at http://projects.dhi.dk/floodrelief/, the project website.

The purpose of this paper is to present some key results of the FLOODRELIEF project related to forecasting uncertainty estimation. These are the development and evaluation of two new ensemble-based uncertainty methods:

- A high-resolution mesoscale ensemble quantitative precipitation forecast (QPF) system for estimating precipitation forecast uncertainty and uncertainty propagation.
- Ensemble-based data assimilation for estimating and reducing hydrological forecast uncertainty.

In parallel with these new developments, the FLOODRELIEF project has developed an Internet-based decision support system for flood forecasting, that can exploit these and other ensemble methods, to provide forecast uncertainties for operational forecasters.

A MESOSCALE ENSEMBLE QPF SYSTEM

Quantitative precipitation forecasts (QPF), based on numerical weather models, can provide substantial improvements in forecast lead time, i.e. the time available to respond before a flood peak occurs. However, there are several challenges when using such QPFs in operational flood forecasting. These include quantifying the uncertainty of the rainfall forecasts, evaluating the impact of uncertainties in precipitation forecasts on the uncertainty in flood forecasts, and deriving QPFs at the appropriate temporal and spatial scales. At the regional scale, the scale at which most floods are managed, effective flood forecasting systems must provide reliable, accurate and timely forecasts for a range of catchments, from small rapidly responding upstream catchments to larger, more slowly responding downstream locations.

The typical approach is to use results from a numerical weather model as input to a hydrological/hydrodynamic model (De Roo *et al*., 2003, Ferraris *et al*., 2002). The uncertainties in rainfall forecasting are often the dominant source of flood forecast uncertainty (De Roo *et al*., 2003; Xuan *et al*., 2004). Recent research, however, shows that using the QPF directly in a hydrological model can result in large biases and uncertainties and that the results must be viewed with caution (Ferraris *et al*., 2002). Ensemble weather forecasts are now available on an operational basis; however, flood forecasting based on 50 or more ensemble members is time consuming and more rapid assessments of forecast uncertainty are needed.

Within the FLOODRELIEF project, a mesoscale ensemble weather forecasting system was developed to investigate some of these issues. The study was carried out in three major steps; (1) set up of a mesoscale weather model for which the QPF performances have been evaluated against other data, such as weather radar; (2) high-resolution QPF ensemble forecasts are derived by downscaling large-scale weather fields with perturbed initial and boundary conditions and applying different microphysics schema, after which both spatio- and temporal- variability of rainfall forecasts are analysed on the catchment scale; and finally (3) the integration of ensemble rainfall forecast for ensemble flood forecasting was carried out.

The mesoscale ensemble weather modelling system consists of: the MM5 weather model (Dudhia *et al*., 2003), the global analyses/forecast data sets from the European Centre for Medium-range Weather Forecasts (ECMWF) (Persson, 2003), and a post-processing system. More details for this system can be found in Xuan *et al*. (2005, 2006). MM5 was configured with four nested domains, for which the grid sizes are 54 km, 18 km, 6 km and 2 km, from the outermost to the innermost domain, respectively. The performance of this system compared well with results from an existing sophisticated nowcasting system, Nimrod (Xuan *et al*., 2004) and radar measurements (Cluckie *et al*., 2006).

During Easter of 1998, the United Kingdom region was hit by some of the worst floods in living memory. Analyses of this flood event have been carried out using the

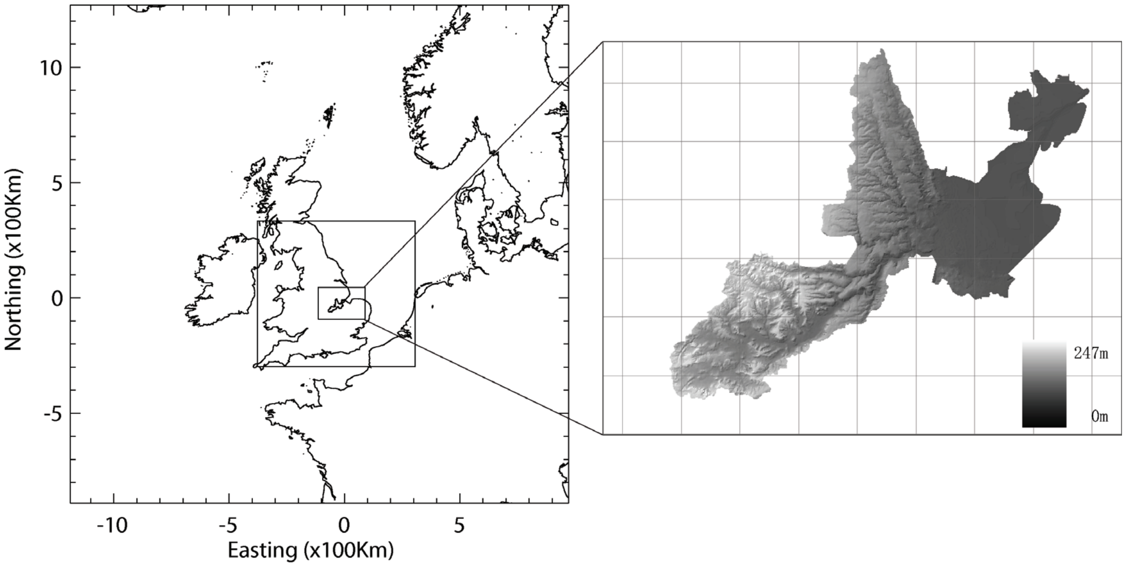


Fig. 1 Model domains for the ensemble QPF system over the Welland and Glen catchment.

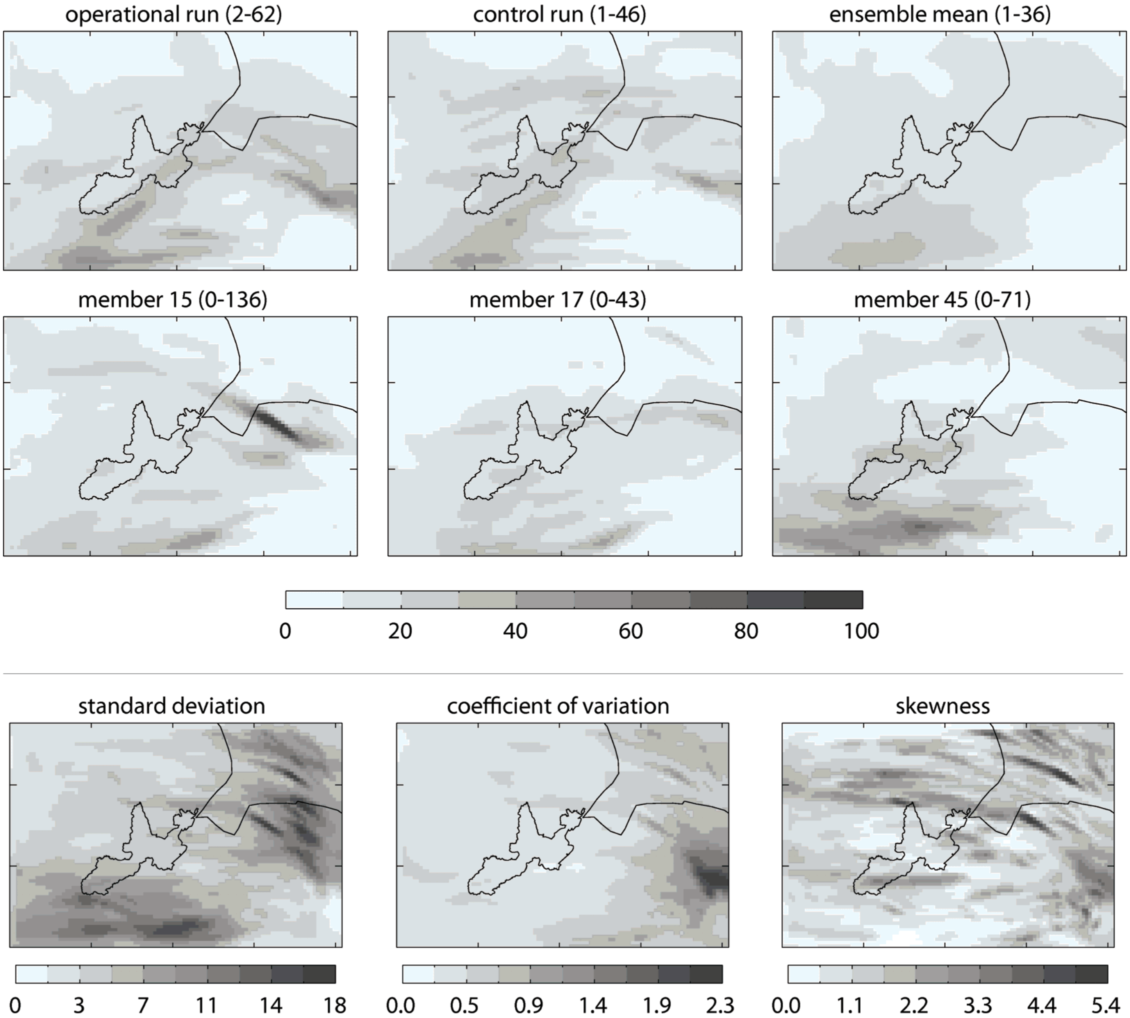


Fig. 2 Rainfall forecast distribution at 2-km resolution.

ensemble QPF system for a test catchment, the Welland and Glen, in the eastern part of UK; see Fig. 1. The ensemble hydrological forecasts are able to provide useful information concerning the nature of the weather system and the confidence levels for the forecast itself (Xuan *et al*., 2005). Sample ensemble members, from the 2-km resolution model; see Fig. 2, show that a large amount of uncertainty exists in the rainfall distributions over both model domains and the catchment scale. Therefore members of an ensemble differ significantly in terms of rainfall forecast distribution. Furthermore, ensemble means are not necessarily the best estimate regarding pattern (Fig. 2). Further work is being carried out to investigate performance using different spatial resolutions.

It should be noted that while this system may perform well for frontal systems, it is still difficult to represent convective storms even at the high resolutions shown here. Indeed, at the 2-km grids or smaller, reformulation of the underlying physics is probably needed to correctly represent small-scale processes. Furthermore, the uncertainties, as well as systematic biases, are quite large and further efforts are needed to improve the quality of such a system. This is illustrated in Fig. 3, which shows results using a distributed hydrological model for the Brue catchment in the southwest of England, coupled with an ensemble meso-scale system. Direct application of the weather models ensemble results in the hydrological model produces results that are substantially different from the observed flows. Alternative rainfall fields were used, first by scaling the model fields using raingauge data, secondly shifting the fields in space using correlation with weather radar (Fig. 3). Spatial scaling with radar was found to give some important improvements. Alternatively, data assimilation methods such as those described in the next section may be useful.

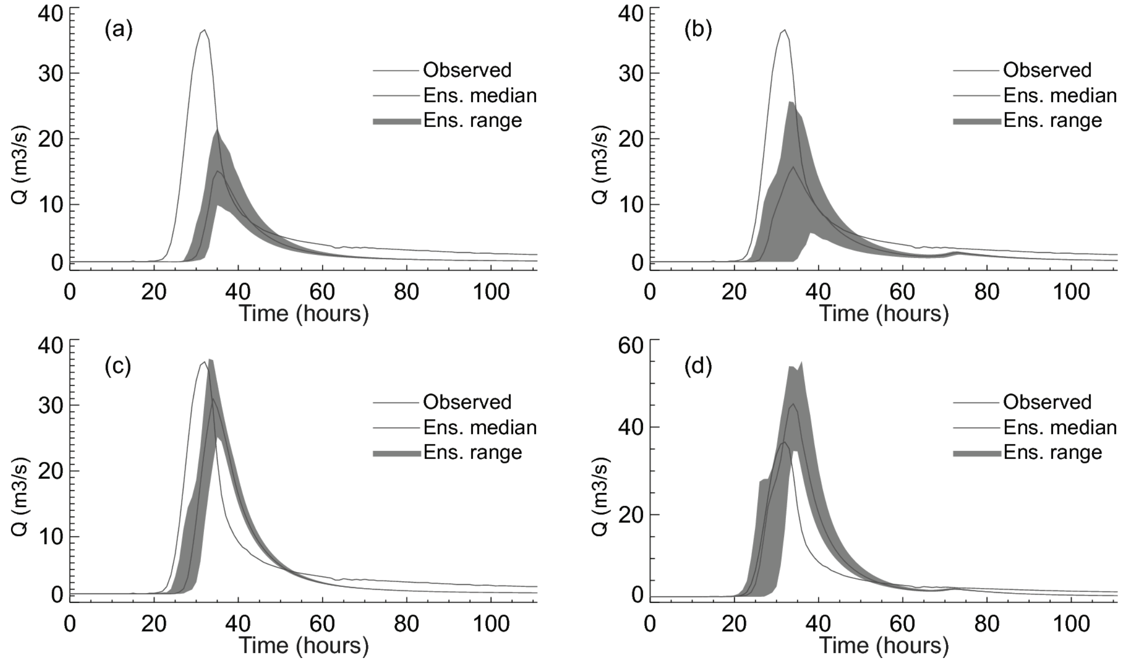


Fig. 3 The ensemble flow forecasts for a single flood event in the Brue catchment for: (a) the direct input of the rainfall ensemble forecasts; (b) the "scaled-up" version; (c) the one with spatial adjustments; and (d) the "scaled-up" one plus spatial correction. The ensemble medians are indicated in each case, while the shaded areas are the spread of ensemble between quantiles 0.1 and 0.9.

ENSEMBLE-BASED DATA ASSIMILATION

Data assimilation, or real-time updating, refers to methods that take into account measurements of water level or discharge in preparing a forecast, adjusting, through a feedback process, the model to match the observations. If based on reliable measurements, this should reduce forecast uncertainty, firstly, by improving the initial state of the system prior to the time of forecast. Secondly, updating is applied to model correction in the forecast period to account for any inadequacy in the model or in the input data. Updating the forecasts on observed streamflow or water levels provides a practical method of reducing the sensitivity of the flow forecasting model to uncertainties in rainfall data as well as taking advantage of the persistence in hydrological flows, to reduce prediction errors. During a flood, both lives and property are at risk and therefore any means to reduce forecast uncertainty is highly desirable. WMO has identified data assimilation as an essential requirement for accurate flood forecasting (WMO, 1992).

Within FLOODRELIEF, a general stochastic framework based on the ensemble Kalman filter (EnKF) has been developed for flood forecast data assimilation (Butts *et al.*, 2004, 2005, 2006; Falk *et al.*, 2006). The EnKF, first presented by Evensen (1994), provides a natural framework for propagating uncertainties through the hydrological and hydraulic models and, through the filtering process, to carry out data assimilation. In the EnKF, an ensemble of realizations is generated at each time step. The variation of the ensemble is, in this study, provided by perturbations of the model boundary conditions but it is straightforward to use ensembles generated from numerical weather models such as the ensemble weather forecasting system described earlier. The Kalman gain is then calculated by means of the ensemble statistics and finally all state variables are updated according to the Kalman filter.

In this paper, data assimilation is performed using the MIKE 11 catchment modelling tool and observations of river discharge, (Butts *et al.*, 2004). These observations are also subject to measurement uncertainty, which can be incorporated in a natural way in the Kalman filter framework. This is illustrated in Fig. 4 for the Blue River basin in the USA. The Blue River is a semi-arid, rapidly responding catchment with little or no baseflow. The discharge measurement is located at the downstream boundary and the estimated uncertainties in the measurements are shown as error bars. Figure 4(a) shows a sequence of forecasts prior to the flood peak. These results show the updated forecasts obtained agree well with the observed flows, within the measurement uncertainty. One of the powerful features of the ensemble Kalman filter is that it also provides confidence intervals for each forecast (Fig. 4(b)).

More recently these methods have been applied to the Waipa basin, a subcatchment of the Waikato River in New Zealand. The Waipa basin has a longer response time than Blue River, with a subtropical climate (van Kalken *et al.*, 2005). Discharge measurements for the Waipa basin were available at five locations, three upstream, one midway in the river system and one at outlet of the subcatchments. The discharge measurements contain information about both the catchment (wetness) and river conditions. Therefore two alternative methods of updating forecasts were compared:

1. Data assimilation or updating is performed only in the river channel assuming uncertainty (coloured noise) in the runoff calculated by a deterministic rainfall–runoff model in each subcatchment. This is denoted HD-KF assimilation.

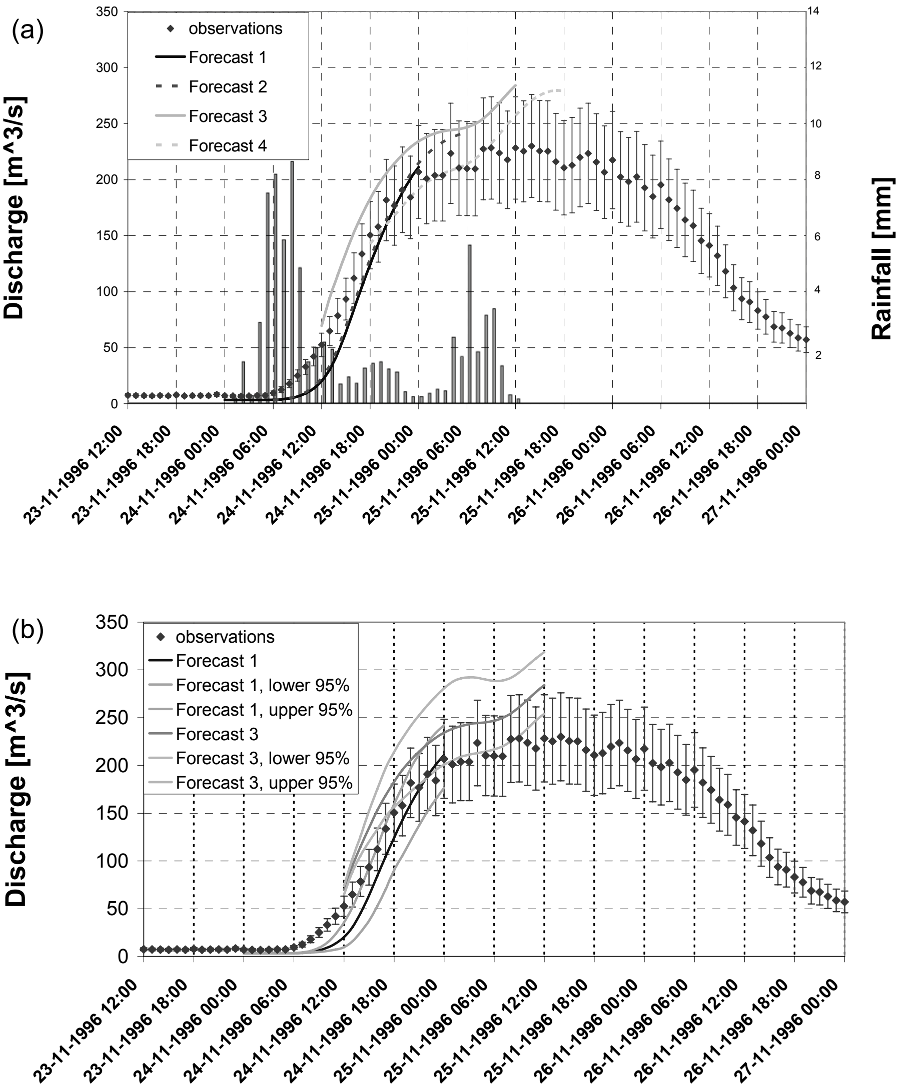


Fig. 4 The ensemble Kalman filter method can be used to: (a) improve forecast accuracy by using the real-time observations, and (b) estimate forecast confidence intervals.

2. Data assimilation or updating is performed in both the subcatchment states and the river channel assuming uncertainties (white noise) in the rainfall (in the present work only the precipitation boundary is considered). This is denoted HD+RR-KF assimilation.

The first method makes changes only in the flows in river channel and assigns uncertainty to the catchment runoff into the river channel. The second method changes both the flow in the river channel and the flows within the rainfall–runoff subcatchments and uncertainty is assigned to the rainfall.

The performance of these two methods is compared in Fig. 5. The graphs on the left show the measured and simulated discharges at the five measurement locations obtained from the original calibration. The downstream catchments are shown at the top and for the three headwater catchments, the corresponding catchment rainfall is

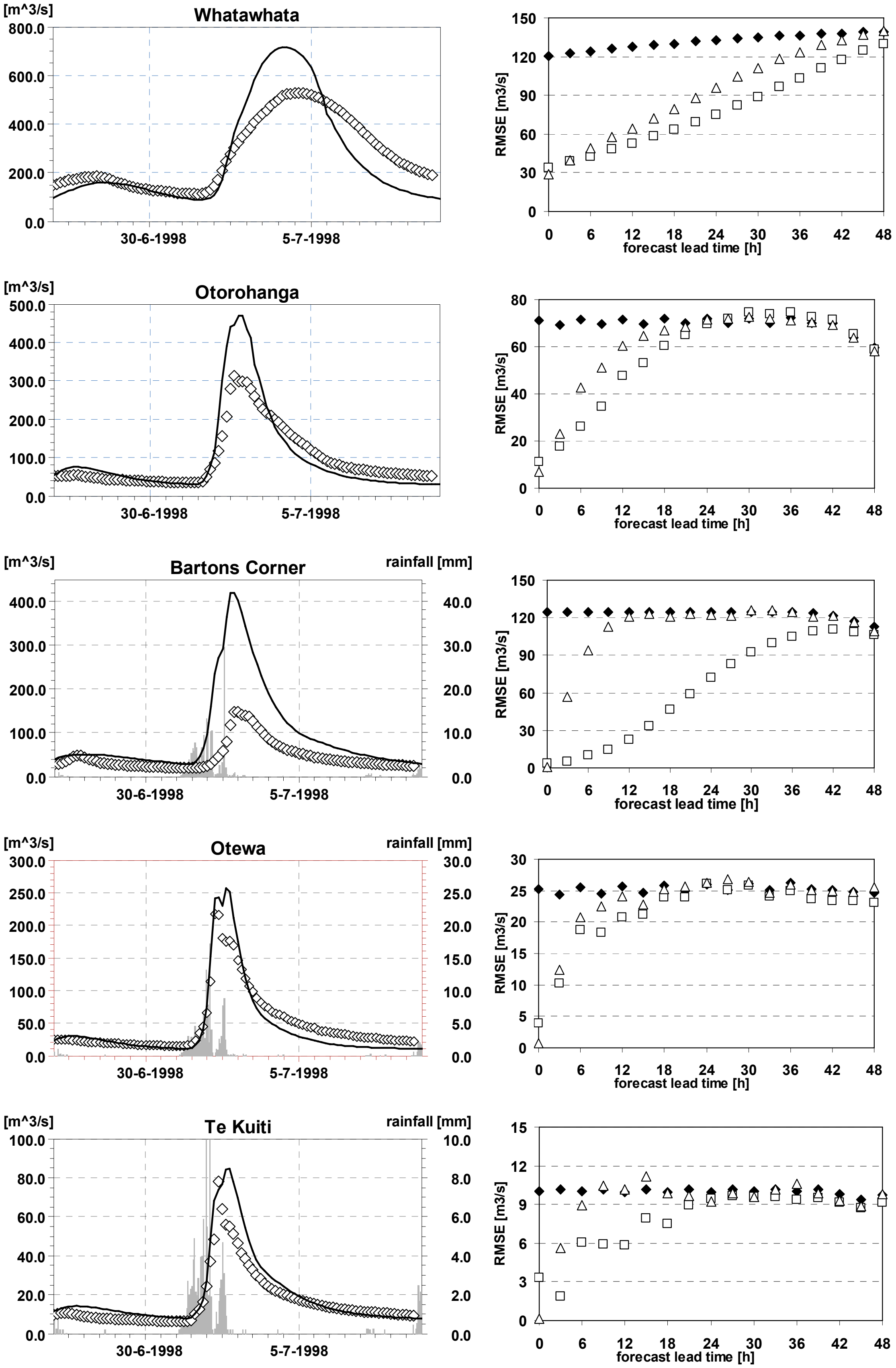


Fig. 5 Simulations (left) and forecast accuracy (right) for a flood event in the Waipa basin.

shown. Significant discrepancies are found between the observed and simulated flows at Barton's Corner and the downstream sites. By applying data assimilation these discrepancies should be reduced.

To quantify the performance of the data assimilation, a sequence of 24 forecasts was made over the flood event and the errors quantified as the root mean squared error (RMSE) as a function of forecast lead time. These are shown on the right hand side of Fig. 5 for each location. The diamonds show the forecast accuracy obtained without data assimilation. In this case, the accuracy is essentially independent of lead time. The application of data assimilation leads to improved accuracy for shorter lead times, for both of the methods investigated.

Updating both in the catchment and the river channel (squares) performs as well as, or better than, updating in the river channel alone (triangles). This is particularly noticeable at the Barton's Corner site where the calibrated model significantly overestimates the catchment flows. Updating within the river channel only corrects the flows for short lead times corresponding to the travel time of the flood wave within the channel. By updating both the river and the channel the accuracy is improved over longer lead times. The physical explanation is that by also modifying the catchment states, the corrections will extend over a longer period, corresponding to the time of concentration (time from rainfall to the generation of runoff) in each subcatchment. This is expected to be a valuable improvement to forecasting accuracy where significant errors in the runoff volume are observed. Such errors often arise because the raingauge network does not properly capture the distribution of rainfall.

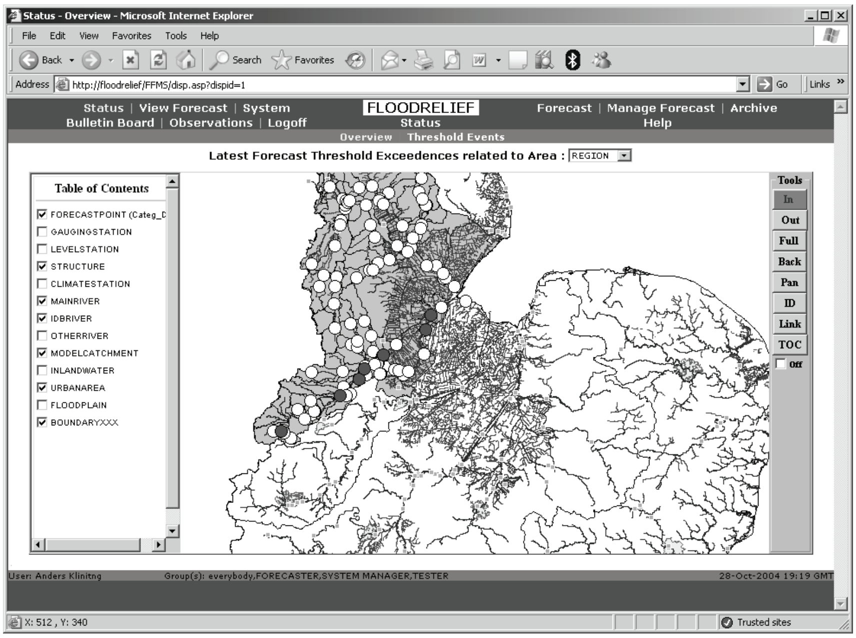
INTERNET-BASED FLOOD DECISION SUPPORT

Flood forecasting decision support encompasses the processes of flood monitoring, flood forecasting, flood warning and real-time decision making. To be effective, flood forecasting systems should provide appropriate decision information in a timely manner to those who need it, where they need it, in a manner that is easy to understand.

The FLOODRELIEF flood forecasting decision support system (DSS) is a regional forecasting system. The key features of the FLOODRELIEF DSS are:

- Provides an intuitive, clear, highly visual display of information to allow rapid assessment and interpretation of forecast information by a wide range of users with different technical backgrounds.
- Includes comprehensive GIS functionality to take full advantage of the available geographical information
- Allows easy access to the forecasting system from a number of different physical and geographical locations, including different offices and, in flood emergencies, operational staff using portable computers at home.
- Contains different forecasting models, ranging from simple station-to-station methods to distributed, state-of-the-art hydrological and hydraulic models, using a general model interface
- Uses the models to provide reliable, timely, accurate forecasts, either automatically or manually, in real time. Reliability ensures that forecasts can be made and accessed under high system loads in flood emergencies. Timeliness and accuracy ensures that the forecasts can be used to prompt and appropriate response.

- Includes comprehensive forecast databases with archiving for forecast analysis.
- Uses a generic external data interface to allow the visualisation and application of a variety of data types from different sources.
- Allows user-defined scenarios to be used to evaluate alternative operation strategies and uncertainty analysis.



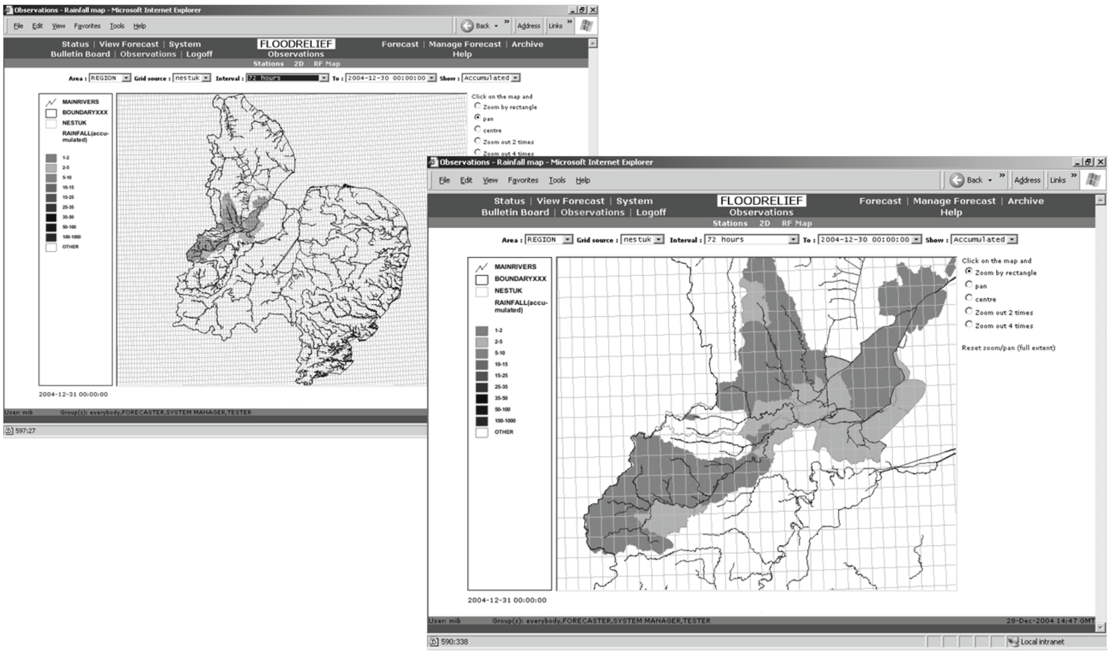
Latest Forecast Threshold Exceedences related to Area : REGION

- ☑ FORECASTPOINT (Categ_D
- ☐ GAUGINGSTATION
- ☐ LEVELSTATION
- ☑ STRUCTURE
- ☐ CLIMATESTATION
- ☑ MAINRIVER
- ☑ IDBRIVER
- ☐ OTHERRIVER
- ☑ MODELCATCHMENT
- ☐ INLANDWATER
- ☑ URBANAREA
- ☐ FLOODPLAIN
- ☑ BOUNDARYXXX

User: Anders Klinitng Group(s): everybody,FORECASTER,SYSTEM MANAGER,TESTER 28-Oct-2004 19:19 GMT

X: 512 , Y: 340

Fig. 6 The Internet-based flood forecasting decision support system developed within FLOODRELIEF.



Area : REGION Grid source : nestuk Interval : 72 hours To : 2004-12-30 00:00:00 Show : Accumulated

Click on the map and
- ○ Zoom by rectangle
- ● pan
- ○ centre
- ○ Zoom out 2 times
- ○ Zoom out 4 times

2004-12-31 00:00:00

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597:27

Area : REGION Grid source : nestuk Interval : 72 hours To : 2004-12-30 00:00:00 Show : Accumulated

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- ○ Zoom out 2 times
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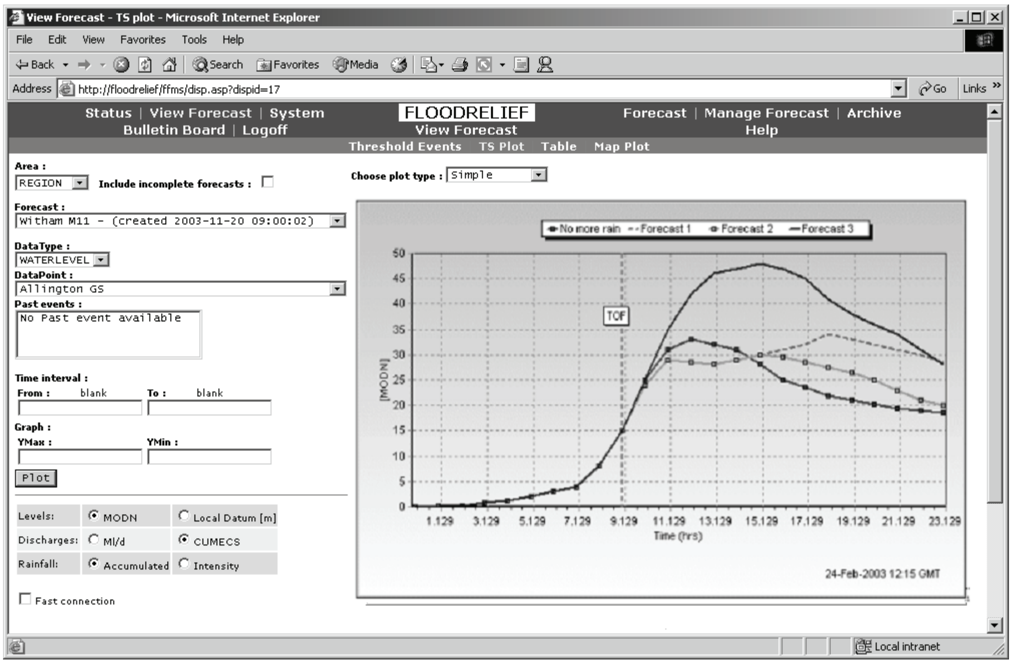
590:338

Fig. 7 Displays of the rainfall forecasts as maps within the decision support system.

Uncertainty is inherent in the flood forecasting process, however very few operational systems use or provide uncertainty information. The strategy adopted in the FLOODRELIEF DSS was to focus on developing practical approaches for operational forecasting. Furthermore, a generic approach was required that could be used for different model tools. Ensemble methods have the advantage that the different sources of uncertainty can be treated in the same way, they are straightforward to apply to different deterministic models widely used in hydrological forecasting, and are consistent with the trend towards ensemble modelling in meteorological forecasting. As the model inputs (e.g. rainfall) are usually the most significant source of forecast uncertainty, these are addressed first.

The decision support system allows for the provision of uncertainty estimates in a number of ways: either from an ensemble of precipitation forecasts from a weather model like the mesoscale QPF system presented earlier, from ensembles generated within the hydrological model, as upper and lower bounds from an uncertainty prediction method, or a best case/worst case scenario analysis. The system allows the user to view the results of a particular weather forecast or ensemble member (Fig. 7). The resulting forecast hydrographs for one or more forecast can be presented together as shown in Fig. 8. This display conveys, in a simple manner, the resulting uncertainty or variation in the flood forecasts at different forecast. In the same manner, alternative scenarios for the operation of flood gates and other flood control structures can be evaluated to ensure the optimal operation of these structures.



Address: http://floodrelief/ffms/disp.asp?dispid=17

Area : REGION
Include incomplete forecasts : ☐
Forecast : Witham M11 - (created 2003-11-20 09:00:02)
DataType : WATERLEVEL
DataPoint : Allington GS
Past events : No Past event available
Time interval :
From : blank To : blank
Graph :
YMax : YMin :
Choose plot type : Simple

Levels: ● MODN ○ Local Datum [m]
Discharges: ○ Ml/d ● CUMECS
Rainfall: ● Accumulated ○ Intensity
☐ Fast connection

Fig. 8 Displays of alternative forecasts to estimate uncertainty or evaluate alternatives.

CONCLUSIONS

This paper presents some results from the EU project FLOODRELIEF, where ensemble-based methods have been used for estimating and reducing forecast uncertainty. The application of a meso-scale ensemble QPF system has shown that ensemble precipitation forecasts are able to provide useful information with respect to the nature of the weather system and the uncertainty of the forecast itself; however, the uncertainties as well as systematic biases are still significant and need to be addressed. A stochastic framework for uncertainty estimation and data assimilation was developed for a combined river and catchment model. An evaluation of several flood events has shown that important improvements in forecast accuracy can be obtained. The results also indicate that data assimilation in both the river and catchment states provides more accurate forecasts over longer lead times than updating on the river channel alone, although further investigations are required. Finally, one of the key deliverables within the FLOODRELIEF project is a real-time decision support system integrating hydrological, meteorological and radar technologies. This system is based on Internet technology making it highly accessible and easy to use. While a generic operational approach has been developed here, for the evaluation and presentation of flood forecasting uncertainty based on ensemble modelling, several challenges still remain. These include the presentation of this uncertainty information in a consistent and easily understood manner for decision-makers, and the difficult task of converting this uncertainty to a corresponding risk.

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