A FLOOD FORECASTING SYSTEM: INTEGRATING WEB, GIS AND MODELLING TECHNOLOGY

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Abstract

Effective operational flood forecasting systems must provide the right information, at the right time to decision-makers responsible for initiating flood response measures and issuing flood warnings. Key information includes the current river levels, meteorological observations and conditions, rainfall estimates for example from weather radar and satellites, as well as quantitative precipitation and hydrological forecasts together with their uncertainty.

To address these requirements a highly accessible internet-based flood decision support system has been developed within the EU project FLOODRELIEF. Designed together with operational forecasters this system provides information in a flexible, efficient and easily understood manner to operational users and decision makers. Using ESRI technology GIS-based maps are used to provide intuitive displays of the flood status, meteorological observations including weather radar and numerical weather forecasts. This decision support system is applied to regional flood forecasting in the FLOODRELIEF study catchment, the Welland and Glen, UK.

INTRODUCTION

Flood forecasting decision support encompasses the processes of flood monitoring, flood forecasting, flood warning and real-time decision-making. Real-time flood forecasting systems, which link weather forecasts, 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 costs in terms of lives, property and the breakdown of infrastructure. In comparison to construction of major flood protection works such as dams, dikes and polders, 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 floods.

The overall aims of EU 5th framework FLOODRELIEF are firstly to develop and demonstrate a new generation of flood forecasting methodologies, which will advance present capabilities and accuracies. Secondly to ensure effective flood management by providing appropriate flood decision support tools that are readily accessible to flood managers, flood warning specialists and in the final end – those affected by the floods. These goals are being achieved by exploiting and integrating different sources of forecast information, including improved hydrological and meteorological model systems and databases, radar, advanced data assimilation procedures and uncertainty estimation, into a real-time flood management decision support tool designed to meet the needs of regional flood forecasting authorities – the FLOODRELIEF Decision Support System.

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. At the outset of the project, the FLOODRELIEF end-users specified end-user requirements for such a forecasting system that addresses the needs of different users. Four main groups of end-users were identified that form a chain from *operational forecasters*, *flood managers and flood warning practitioners*, *professional partners and emergency services* to *those directly affected*, Butts and Khatibi, (2003). Subsequently the FLOODRELIEF end-users examined in a systematic fashion what type of information each of these user groups would like to see and how they would like them presented. In the

particular, detailed end-user requirements for operational end-users were developed for the integration of meteorological and radar and uncertainty data into flood forecasting systems, Price et al., (2003). These reviews were then used as the basis for developing the FLOODRELIEF decision support system, (http://projects.dhi.dk/floodrelief/).

This paper focuses on two key areas of information that are crucial to flood forecasting during extreme flood events – numerical weather modelling and forecast uncertainty. Using meteorological observations and quantitative precipitation forecasts to produce hydrological flood forecasts provides valuable increases in lead-time that can be exploited to mitigate the effects of a flood event. This is the case for both flash floods and also more extensive basin-scale floods. However while the value of accurate meteorological forecasts is widely recognised real-time flood management decisions must be based on an understanding of the uncertainties and associated risks. Currently very few systems provide uncertainty information to operational users. In the FLOODRELIEF DSS comprehensive facilities for accessing and presenting both meteorological observations and numerical weather forecasts are available. The system has been integrated with a highly portable, low cost operational numerical weather forecasting system - THOR. The THOR system has been developed within the FLOODRELIEF project to provide quantitative precipitation forecasts at different resolutions using dynamical downscaling. Ensemble forecasting using different forecasting inputs provides a flexible method of estimating uncertainty. For example, alternative rainfall forecasts using meso-scale meteorological forecasts or weather radar forecasts can be used by operational forecasters to models to estimate an uncertainty range. In this manner a direct and intuitive estimate of forecast uncertainties that can be communicated to flood managers and decision-makers, is achieved.

THE FLOODRELIEF DECISION SUPPORT SYSTEM

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 an 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.

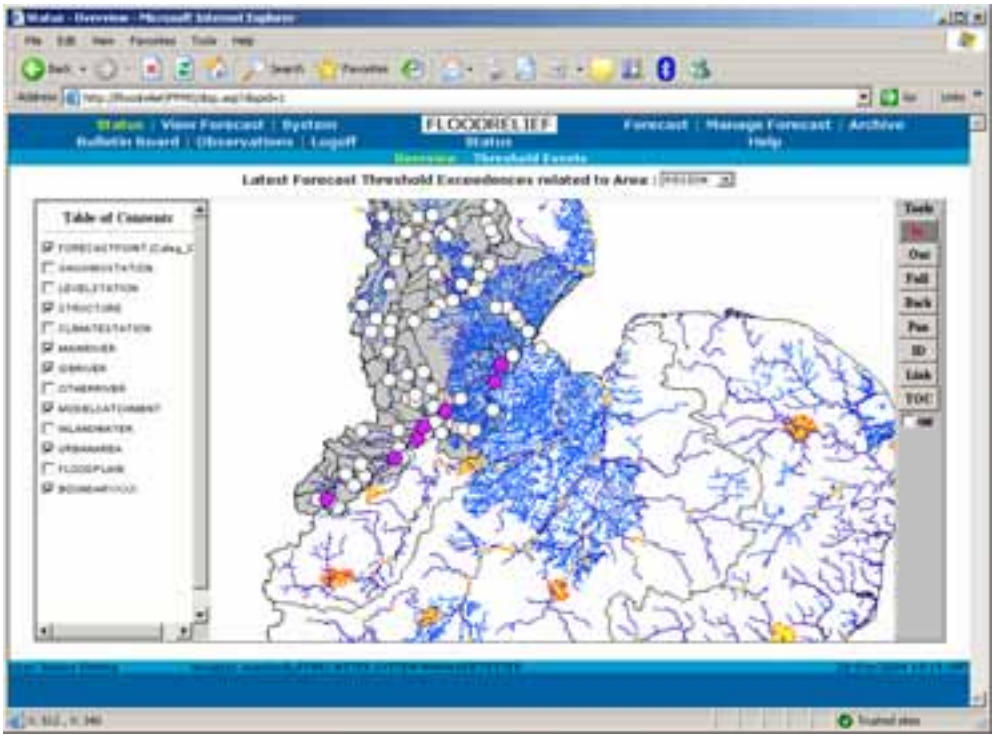

Figure 1 *Web-based user interface of the FLOODRELIEF Decision Support System*

The user interface is based on internet technologies, including the use of state-of-the-art GIS tools to provide map-based displays of forecast information and GIS functionality, see Figure 1. .

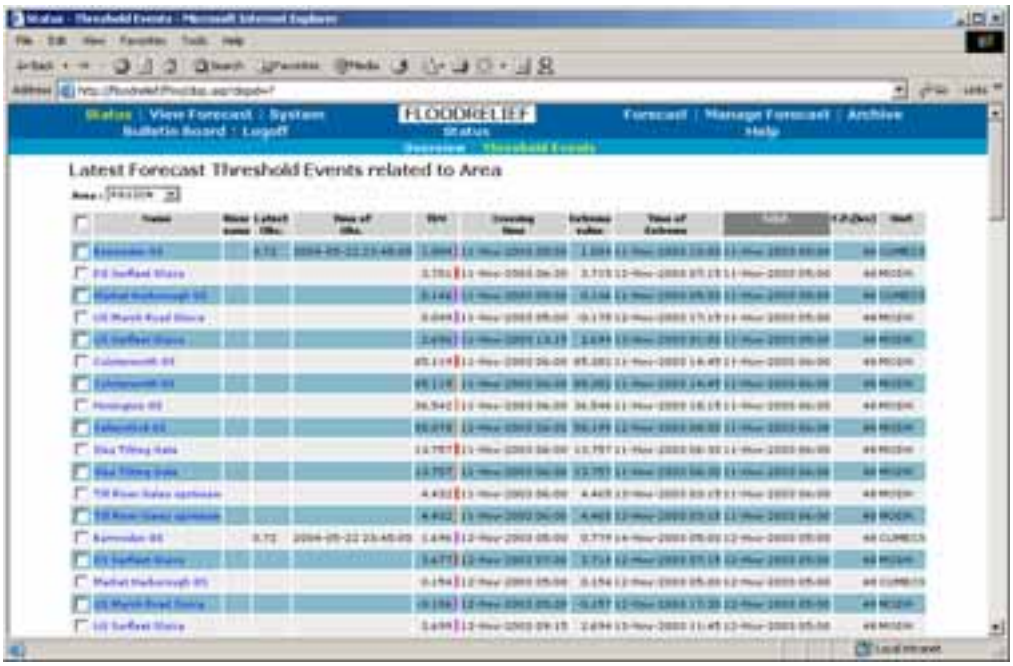

Figure 2 *Threshold levels used for flood warning or initiation of flood control activities*

The use of a web-based user interface has several advantages. Firstly the system can be accessed across large geographical areas. As the Internet is so widespread, navigation is

straightforward and requires little training to understand. In developing this system, the different displays of information were designed together with the end-users to ensure the displays are easy to understand and the information they contained was appropriate. Using thresholds, flood forecasts of flow, water level and velocity can be used to provide generate flood warning or to initiate other flood mitigation measures such as alerting operational staff or using flood control structures, Figure 2.

INTEGRATING NUMERICAL WEATHER MODEL INFORMATION

The value or potential benefit of a flood forecast depends on three factors. Firstly its accuracy, which in turn depends on the accuracy of the forecast data, the observational data and the hydrological modelling and updating procedures. Secondly the magnitude of the lead time it provides before critical levels are reached. Thirdly, value of the forecast depends on the effective use of the forecast information, for example, in initiating flood warnings and evacuating people and livestock.

Accurate quantitative precipitation forecasts can provide valuable increases in forecast lead time and therefore permit more effective flood management and flood warning. It is widely recognised that increases in forecast lead time are crucial for small rapidly responding catchments and for flash flooding. However increases in both forecast accuracy and lead time can also have important benefits in larger basins. New opportunities for applying numerical meteorological models for quantitative precipitation forecasting exist today in Europe that did not exist a few years ago. These models provide not only useful qualitative information about approaching flood-producing storms but more importantly quantitative precipitation forecasts (QPF's).

Within FLOODRELIEF a new version of the THOR integrated weather and air pollution forecast and management system, (Brandt, 2001a, b, & c; 2003) based on the Eta model has been developed and integrated into the FLOODRELIEF DSS, see http://thor.dmu.dk. The *qualitative* information in terms of maps of precipitation, evapotranspiration, wind speed, snow cover, etc that may be of interest to the operational user are often already available within a weather forecasting system so the FLOODRELIEF DSS provides facilities to collect a subset of the processed information generated by a weather forecast model, providing only those relevant to a flood forecaster, Figure 3.

The *quantitative* numerical weather forecast data needs to be made available to both the operational forecaster and the flood forecasting models. The key meteorological forecast variable for flood forecasting is of course the quantitative precipitation forecasts. The precipitation forecasts from the weather forecasting are provided as grid data in a curvilinear (latitude-longitude) system. The weather model grid and the distribution of rainfall over the model area provide useful information of about the areas at risk, Figure 4. The data interface is an external data API that provides a generic data interface to support the import of the weather forecasting data. These data are then made available to the forecaster via the FLOODRELIEF user interface and are made available to the flood forecasting models by the model interface. The model interface provides the meteorological information in a form that can be used in operational flood forecasting by the hydrological forecast model, including the transformation of the grid-based rainfall to subcatchment totals, Figure 4.

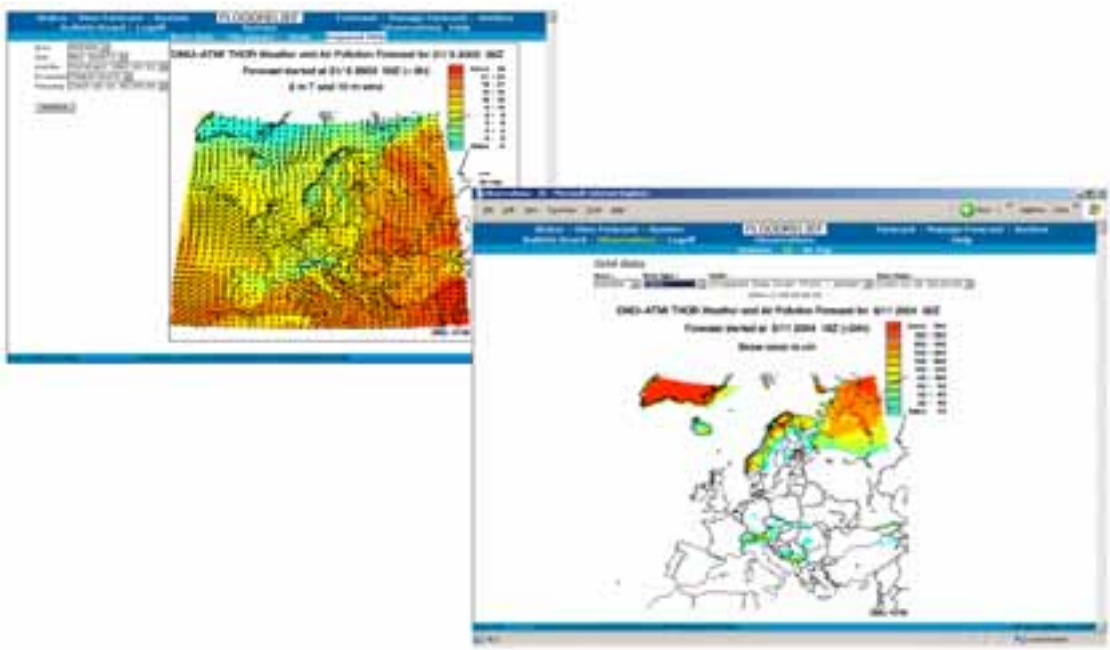

Figure 3 *Qualitative meteorological information such as temperature and wind direction (left) or snow cover (right) is made available to the operational forecaster within the FLOODRELIEF user interface*

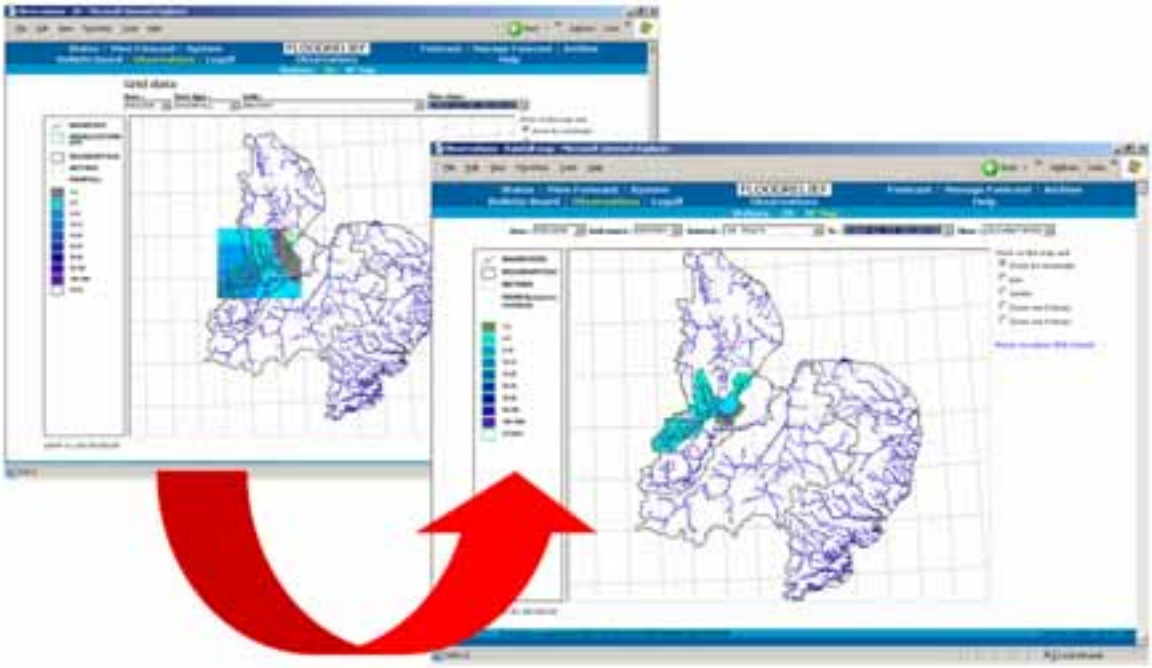

Figure 4 *Transformation of the (curvilinear) grid rainfall forecasts to catchment rainfall totals for the hydrological flood forecasting models*

High resolution meteorological modelling

To represent more accurately the spatial variation of rainfall patterns and to forecast rainfall over smaller areas within a catchment or region, recent research has focussed on downscaling meteorological models to hydrological scales. The scale of operational meteorological models is often larger than the hydrological scale of interest. Within FLOODRELIEF investigations are being carried out to determine the benefits of using dynamical downscaling of numerical weather models for flood forecasting, Skjøth et al., (2005). Higher resolution results can be obtained by increasing the resolution over the entire domain which is very computationally demanding or using statistical downscaling which does not take advantage of the description of known physical and meteorological processes on the local scale. Therefore, dynamical downscaling where dynamical weather forecast models are used at high spatial scales using nesting techniques is preferable. Operational nested precipitation forecasting down to less than 4 km is being investigated within the two FLOODRELIEF study basins, the Odra River in Poland and the Welland/Glen rivers in the UK. The FLOODRELIEF DSS allows the user view or use the different model results at different resolutions, see Figures 4 and 5.

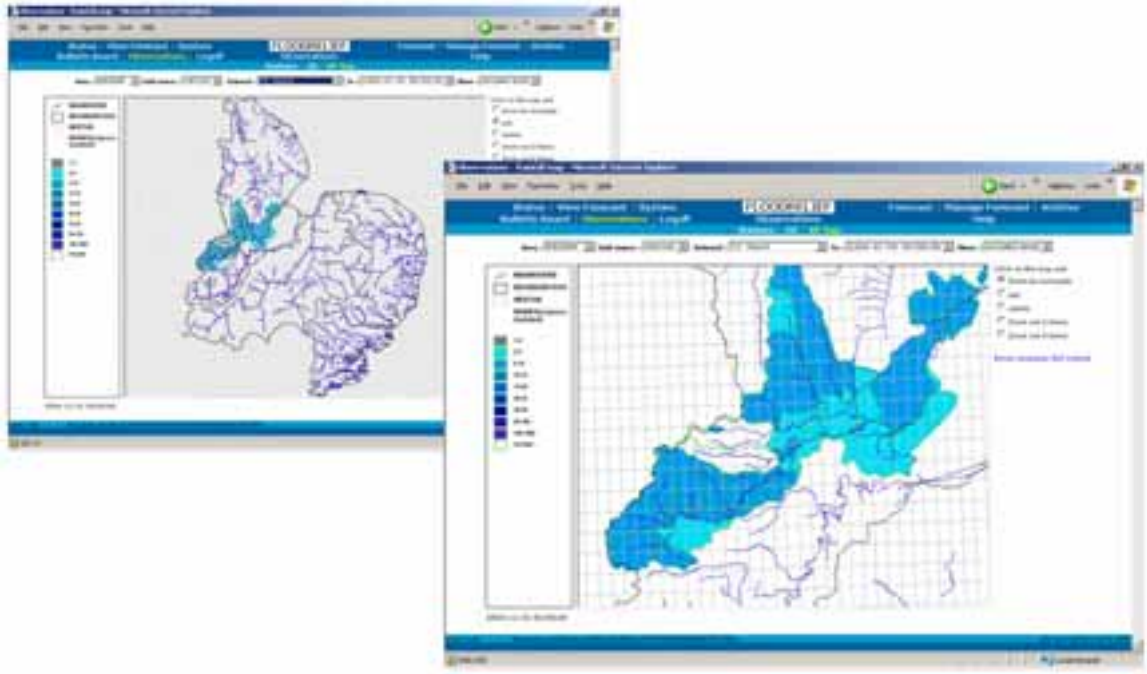

Figure 5 *Quantitative precipitation forecasts at different resolutions can be viewed and used for forecasting. The GIS tools can be used to examine the variability over the area of interest.*

INTEGRATING FORECAST UNCERTAINTY INFORMATION

Uncertainty is inherent in the flood forecasting process, Butts et al. (2002). However, very few operational systems use or provide uncertainty information. Flood forecasting decision makers are increasingly recognising that estimation of uncertainties and risks are an important aspect of the decision-making process, Cadman et al., (2005). Butts et al., (2004) classify the sources of hydrological modelling uncertainty into the following main groups

- random or systematic errors in the model inputs (boundary or initial conditions)
- random or systematic errors in the recorded output data used to measure simulation accuracy
- uncertainties due to sub-optimal parameter values
- uncertainties due to incomplete or biased model structure

In the case of forecasting modelling additional contributions to forecast uncertainty and accuracy need to be considered. The most important of these are the uncertainties associated with forecasted inputs such as quantitative precipitation forecasts. In addition the efficiency of the data assimilation may have a significant effect on forecast accuracy, (Madsen et al., 2000, Butts et al., 2006). Finally unpredictable effects like such as processing or human errors, channel blockage and dyke failure and the like may have significant local impact on forecast accuracy.

There are several challenges to be addressed in the application of uncertainty information in flood forecasting. They include the following steps

1. quantifying the magnitude of the uncertainty sources
2. evaluate the impact of the different sources on the flood forecast accuracy
3. provide this uncertainty information in a manner that can be understood by operational forecasts and decision makers
4. evaluate the impact of the uncertainty on the decision making and management options

The strategy adopted in the FLOODRELIEF decision support system was to focus on developing practical approaches for operational forecasting. As the model inputs (e.g. rainfall) are usually the most significant source of forecast uncertainty these are addressed first. Furthermore a generic approach that could be used for different model tools was required. To satisfy these requirements an ensemble-based approach was adopted. Ensemble methods have the advantage that the different sources of uncertainty can be treated in the same way, it is straightforward to apply to the deterministic models widely used in hydrological forecasting and are consistent with the trend towards the use of ensemble modelling in meteorological forecasting.

The decision support system allows for the provision of uncertainty estimates in a number of ways; either from an ensemble of precipitation forecasts, from ensembles generated by the hydrological model, as upper and lower bounds from an uncertainty prediction method or a best case/worst case scenario analysis. An example of such an ensemble is the forecast obtained using the different resolutions provided by the weather forecast system. The system generates multiple forecasts and allows the user to view the results of the weather forecast ensemble and the resulting flood forecast ensemble or confidence interval. In the example shown here we can view the rainfall forecasts resulting from different spatial resolutions in the weather forecasting model, Figure 6. The estimated forecast rainfall and the resulting forecast hydrograph are shown as ensembles, Figure 7. This display conveys, in a simple manner, important information about the weather forecast uncertainty and in the same plot the resulting uncertainty or variation in the flood forecast at different forecast points can be examined.

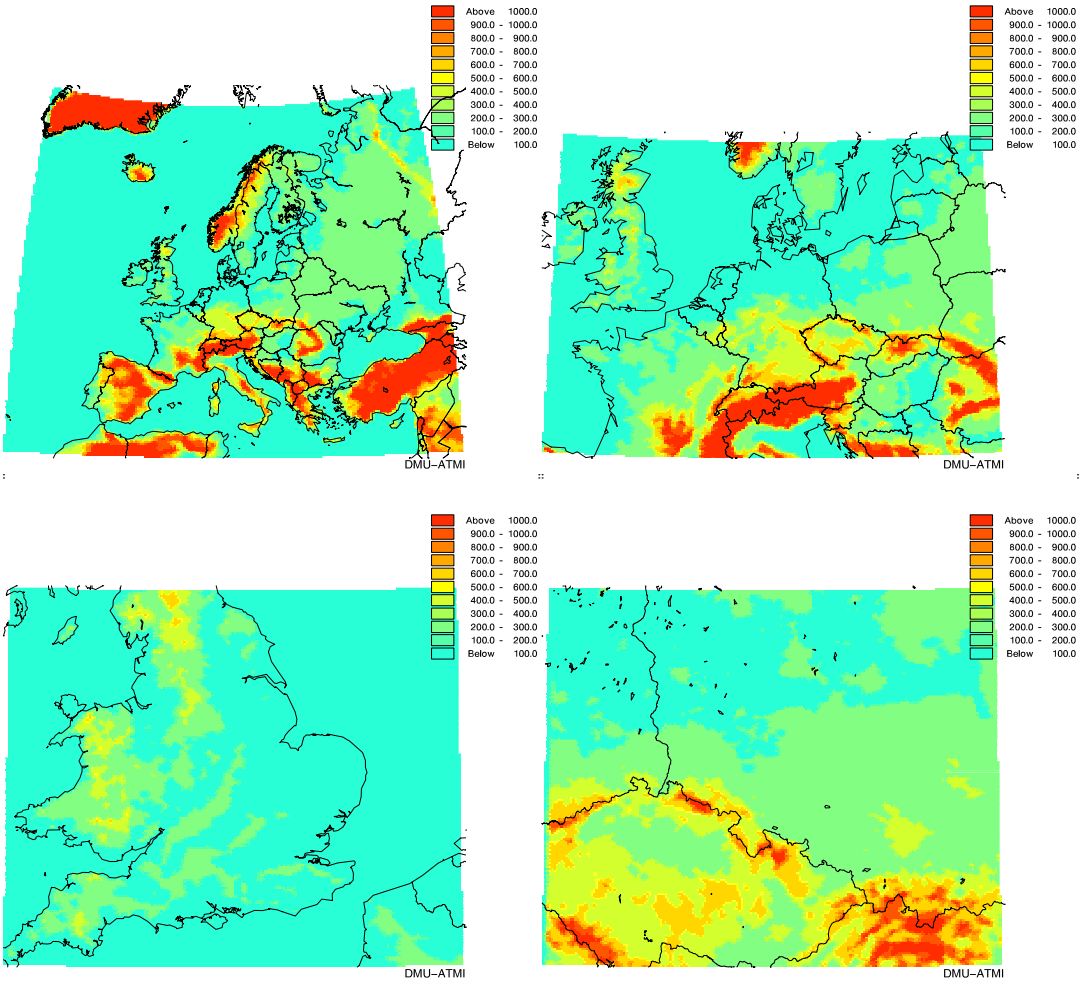

Figure 6 *The nested model domains used within the FLOODRELIEF project. The upper figures show the European model domain and the first level nest. The lower figures show the second level nests over the United Kingdom and Poland. The colour scale shows the topography.*

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.

CONCLUSIONS

While the value or benefit of a flood forecast depend on a number of factors, such as its accuracy, timeliness, reliability a key factor is the effective use of the forecast information, for flood monitoring, flood warning, the operation of flood protection structures and the evacuation of people and livestock. This requires appropriate decision-making information in a timely manner to those who need it, where they need it, in a manner that is easy to understand. The need to address these requirements has led to the development within EU 5th framework project FLOODRELIEF of an internet-based decision support system to provide highly accessible real-time flood management tool.

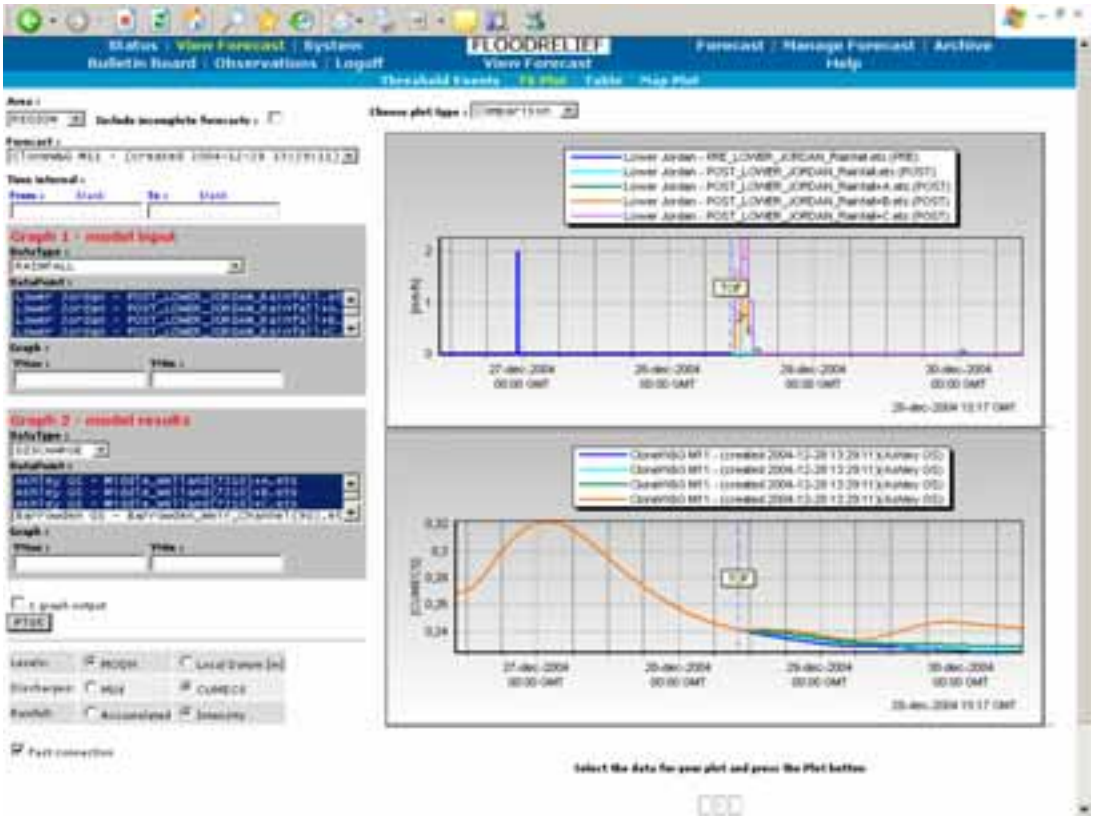

Figure 6 *Display of an ensemble of precipitation time series for a catchment and the resulting ensemble of flood forecasts*

In the FLOODRELIEF project, a real-time decision support system integrating hydrological, meteorological and radar technologies was developed. This system is based on internet technology making it highly accessible and easy to use. The displays of information within this user-interface were designed together with operational end-users to create a system to match their needs. Using ESRI technology GIS-based maps are used to provide intuitive displays of the flood status, meteorological observations including weather radar and numerical weather forecasts. New opportunities for applying numerical meteorological models at greater temporal and spatial resolution exist today that did not exist a few years ago. These models not only provide useful qualitative information about approaching flood-producing storms but more importantly quantitative precipitation forecasts QPF's. These QPF provide valuable increases in forecast lead time to allow more effective decision making. By integrating this system with the THOR weather forecasting system, the FLOODRELIEF DSS provides both qualitative and quantitative meteorological information for flood forecasting.

Uncertainty is inherent in the forecasting process and there is growing recognition by flood forecasters and managers that estimation of uncertainties is an important aspect of the decision-making process. A generic operational approach has been developed here for the evaluation and presentation of flood forecasting uncertainty based on ensemble modelling. However several challenges still remain including 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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