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Visualizing flood forecasting uncertainty: some current European EPS platforms – COST731 working group 3

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Abstract

Cooperation in Science and Technology (COST) funding allows European scientists to establish international links, communicate their work to colleagues, and promote international research cooperation. COST731 was established to study the propagation of uncertainty from hydrometeorological observations through meteorological and hydrological models to the final flood forecast. Our focus is on how information about uncertainty is presented to the end user and how it is used. COST731 has assembled a number of demonstrations/case studies that illustrate a variety of practical approaches and these are presented here. While there is yet no consensus on how such information is presented, many end users do find it useful. Copyright © 2010 Royal Meteorological Society

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Keywords: **flood forecasting; uncertainty; communication; end users; ensemble; visualizing**

1. Introduction

Cooperation in Science and Technology (COST) projects are the oldest existing mechanism used by the European Commission for funding research cooperation. These projects are called 'Actions' and COST731 (http://cost731.bafg.de) is one such Action studying the propagation of uncertainty through the flood forecasting chain, from atmospheric models and remote data collection through to hydrological models estimating flood flows and hydraulic models producing maps of inundation depths, extent, timing, and duration. The progression of uncertainty from atmospheric observations into numerical weather prediction and from thence into hydrological models is treated in two companion papers (Rossa *et al*., 2010; Zappa *et al*., 2010) The Action formed a working group to examine how uncertainty is communicated to end users and held a special workshop in Dublin in November 2008 which demonstrated a number of internet-based platforms, most operational and many using some form of ensemble prediction system (EPS), for delivering both the flood forecast and also uncertainty information to the user. There were a wide variety of approaches to presenting uncertainty information to the end user. Most approaches accept that the 'spaghetti plots' generated from EPS are not appropriate, but each differs in how to represent and communicate the probabilistic information they contain. The opinions of the workshop participants on the platforms presented and on the communication of uncertainty information were sought at round table discussions following the formal presentations and formed part of the meeting report. While users did want to have uncertainty information, none was willing to claim that it improved their decision performance. To illustrate the variety of approaches, some of the platforms demonstrated are described below, together with others that were accessed later.

2. MAP D-PHASE demonstration platform

MAP D-PHASE (*Demonstration of Probabilistic Hydrological and Atmospheric Simulation of flood Events in the Alpine region*) was a project focused on demonstrating progresses in forecasting heavy rainfall and flood in the alpine region (Rotach *et al*., 2009; Zappa *et al*., 2008). The project had an explicit focus on the involvement of end users and developed an innovative visualization platform that was run during the whole demonstration period (June to November 2007) and which, with reduced content, continued beyond the end of the project. This visualization platform has four different levels.

- *Level 1*: General alerts based on heavy rainfall for all six target areas in the Alpine region.
- *Level 2*: General alerts based on heavy rainfall for all six target areas in an Alpine subregion

Figure 1. The river Sihl flowing below the central railway station of Zürich. Two of the five channels are closed by tide gates to allow the construction of new track below the river. Picture by A. Badoux, WSL.

accompanied by a table displaying the alert of each individual atmospheric model for every target area.

- *Level 3*: Detailed alerts on heavy rainfall and discharge for an individual hydrological impact area. A table displays the detailed alert status of every hydrological and atmospheric model for each forecast hour.
- *Level 4*: Online model outputs in the form of weather maps and discharge hydrographs.

In addition, a series of nowcasting platforms were linked to the platform to provide support for real-time decision making during an event. The end user opinions on the platform were collected in a series of workshops and they appreciated the real-time availability of high-end weather radar information (Germann *et al.*, 2009).

As an example, the information given by the platform on the 15 July 2009 is shown in the animated GIF provided as supporting material. This shows a series of screenshots of the MAP D-PHASE platform showing the progression of flood warnings over a series of days for an area centered on Switzerland. It also shows the corresponding discharge predictions.

3. City of Zürich platform

The Sihl basin (336 km^2) is a very challenging and flood prone river basin and constitutes a serious threat to the central railway station of Zürich, the most populated city of Switzerland. The river flows through five enclosed channels below the station (Figure 1). In the upstream part of the basin, a concrete dam impounds waters from a headwater sub-basin of about 155 km^2. The waters in the dam are managed by a private hydropower company, however, the other headwater sub-basins are prone to flash-floods.

Between 2008 and 2011, a new underground railway station will be built below the River Sihl and the works temporarily reduce the capacity of the Sihl riverbed by 40%. If an unexpected flood occurs during the works, the potential for damages exceeds 1 billion Euros and the lives of the people living, traveling, and working in the environs of the station would be endangered. For this reason, the local authorities decided to implement a real-time flood warning system associated with the construction works.

The flood forecast system is an operational implementation of the hydrometeorological modeling chain implemented for MAP D-PHASE (Rotach *et al.*, 2009; Zappa *et al.*, 2008). The hydrological model PREVAH (Viviroli *et al.*, 2009) is forced by the output from both deterministic and ensemble numerical weather prediction models. Once a flood forecast is produced, the various options for flood control and protection at Zürich central station are evaluated by experts. When necessary, decisions are taken by the local administration following discussions with a panel of persons composed of stakeholders (local administrations, Swiss federal railways, insurances, members of the hydropower company managing the Sihlsee, and those responsible for constructing the new railway station), meteorologists, and hydrologists. One option is to order a controlled drawdown of the upstream lake. However, to be effective, this should be ordered at least 2 or 3 days before the serious flood is expected and it may trigger substantial financial penalties if no storm occurs because of the energy lost. A second option for flood mitigation is controlled flooding of two sections of the five channels below the railway station that are normally closed to allow construction work in these channels. In this case, the building contractor could lose up to 2 weeks of work, which would also incur significant financial loss. In addition, it takes the contractor from 6 to 12 h to remove machinery and materials from the sections to be opened and a similar amount of time to remobilize and these inflict a delay in the construction schedule. Thus, this situation involves a large group of stakeholders with diverse interests and there are significant financial implications both for acting on false alarms and for not predicting a severe flood.

The main interface between the modelers and the end users is a tailored visualization platform integrating information from different modeling systems (atmospheric and hydrological ensemble predictions systems) and observation networks (weather radar, discharge station, snow maps, raingauges). The user can access the data of most recent forecasts and interpret them in order to improve his or her basis and background knowledge for decision making. Levels of alert are given for ten control points with the catchment. The different alert levels were determined from prior model simulations of the catchment and river system with a view to detecting in due time which measures have to be taken in order to minimize the risk of damages for the environs of Zürich central station, including the construction site itself.

4. Swedish flood forecasting platform

The basis of the flood forecasting system at the Swedish Meteorological and Hydrological Institute (SMHI) is the HBV model (Bergström, 1976; Lindström *et al*., 1997). The model has subroutines for interpolation of input meteorological data as well as estimation of snow accumulation and melt, evapotranspiration, soil moisture, and discharge at the catchment outlet. A simple routing scheme is used to transfer the outflow to downstream catchments. The model is semi-distributed, i.e. the catchment may be divided into land classes specified by altitude and land use. The model has a number of free parameters that may be automatically calibrated (e.g. Lindström, 1997).

In 2004, a production system for hydrological ensemble forecasts was put into operational use at the SMHI flood forecasting service (Johnell *et al*., 2007). The system is based on the meteorological ensemble forecasts issued at European Centre of Medium-range Weather Forecasts (ECMWF). For each forecasted catchment, the precipitation and temperature in the ECMWF forecasts from the model grid box covering the catchment are directly applied as inputs to the HBV model, set up and calibrated (using historical observations) for the catchment.

The HBV model is run using all 51 ECMWF precipitation and temperature forecasts (control forecast +50 ensemble members) as input, generating an ensemble of 51 discharge forecasts for up to 9 days ahead. The ensemble discharge forecasts are autoregressively updated by estimating the discharge error at a certain day in the forecast as a function of the error at the start of the forecast (e.g. Lundberg, 1982).

The discharge ensemble is processed statistically to generate forecast products that are stored and delivered to other components of the flood forecasting system. The main processing is to transform the ensemble members into five statistical quantiles, representing 2, 25, 50, 75, and 98% nonexceedance probabilities, respectively. These quantiles are transferred to the graphical interface WebHyPro, which is used to visualize discharge forecasts. Figure 2 shows the two main ways in which ensemble discharge forecasts are displayed, either as a time series of the future forecasted discharge in a single catchment (Figure 2(a)) or as a map showing the areas in which a certain warning level, related to the severity of flooding impact, is forecasted to be exceeded with a certain probability (Figure 2(b)).

The ensemble forecasts have been recently evaluated, by (1) comparing them with an operational deterministic forecast and (2) by evaluating the statistical properties of any bias in the calculated quantiles (Olsson and Lindström, 2008). A general conclusion was that the spread in the ensemble of discharge forecasts is systematically underestimated, and different post-processing methods are being explored to adjust the estimated quantiles.

5. Finnish flood forecasting platform

In Finland, the watershed simulation and forecasting system (WSFS) (http://www.environment.fi/waterforecast) is used for flood forecasting and warning (Vehviläinen *et al*., 2005). WSFS produces daily hydrological ensemble forecasts and warnings for over 600 river and lake points. WSFS covers an area of 390 000 km^2 including Finland and cross-boundary watersheds. The uncertainty in the hydrological forecast is estimated by using 52 EPS weather forecasts from 10 to 100 days ahead and historical weather data as input to the hydrological model and creating probabilistic hydrological forecast for 10, 100, and 360 days ahead (Figure 3). This shows the period from January 2009 to December 2010 with forecasts of lake water level from the end of December 2009. The green area shows the 50% probability band, the red and green areas together show the 90% probability band, and the green, red, and yellow together show the entire range of the ensemble. The area shaded gray shows the long-term climatic range. The thick black line shows the measured levels, the blue line shows the estimated future levels and the pink line shows the long-term median value. The forecast is also delivered as written text including probabilities and dates for peak water level/discharge values. Flood warnings are given as probabilities (25% quantiles) of exceeeding certain water levels, discharges, or lake outflow limits. Warning sites are displayed on a map as well as high water level areas.

6. German flood forecasting platforms

The EU FP-6 funded project PREVIEW developed tools and methods for dealing with a broad range of environmental risks, including floods (www.preview-risk.com) and has provided a number of examples of

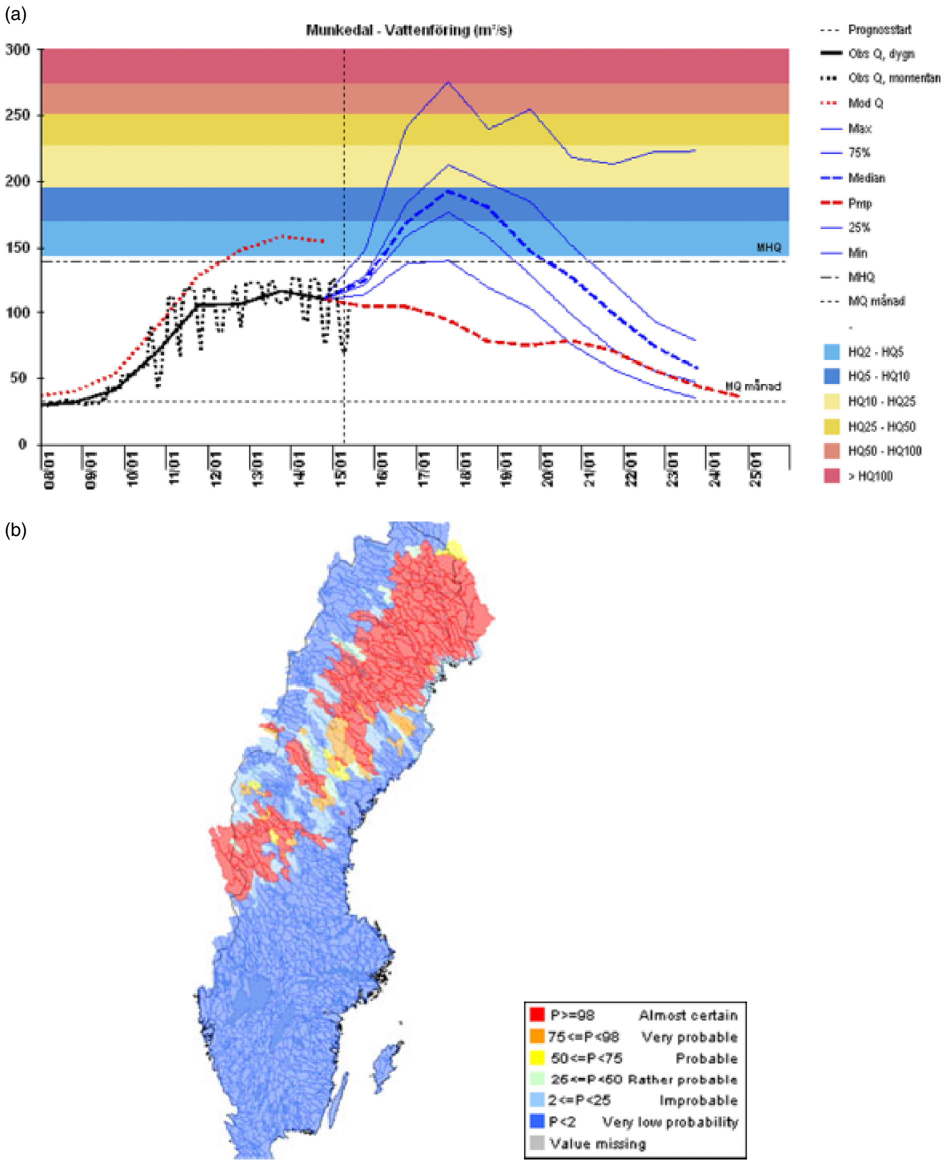

Figure 2. Examples of graphical ensemble forecast products in WebHyPro: ensemble quantiles for a single catchment (a) and spatial probability of reaching a certain flood warning level (b).

the integration of information tools for specific rivers (http://www.floodrisk.eu/FloodServer/) which demonstrate different methods of communicating flood risk information. Flood hazard was addressed in four ways.

- Medium-range plain flood forecasting and early warning (forecast lead time >3 days).
- Short-range plain flood forecasting (forecast lead time <3 days) and flood risk management.
- Very short-range high-resolution flash flood forecasting (forecast lead time <36 h).
- Northern flood forecasting (forecast lead time 1–10 days).

Each takes into account the specific nature of the flood generation processes, the different spatial and temporal scales involved as well as the respective damage potential. Each flood type is dealt in a specific flood warning and flood response service.

The short-range plain flood forecasting service for the Bavarian part of the River Danube is a useful case study for flood forecasting based on meteorological ensembles. The benefits of the forecasts were validated by the users at stakeholder workshops as well as by questionnaires. This gives detailed feedback related to each delivered service. The end users covered the whole bandwidth of administration that has to deal with floods, including

- Flood forecasting centers: responsible for flood forecasts.
- Regional and local water management authorities: regulatory authorities, responsible for flood warnings and flood alerting plans, operation of reservoirs, maintenance of hydraulic structures/constructions, advice of crisis management groups during floods.
- Regionally and locally responsible civil protection authorities, crisis management groups: control all

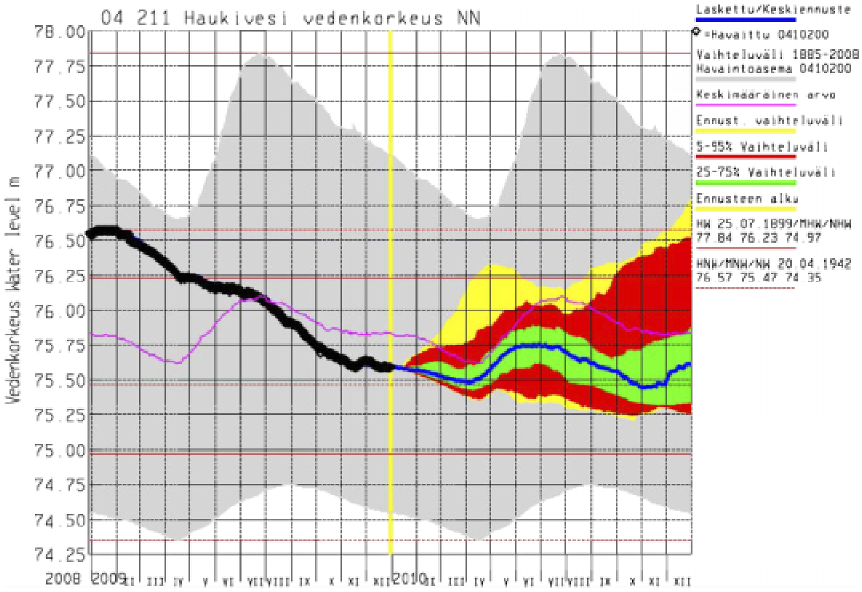

Figure 3. Water level forecast (12 months) for Lake Haukivesi where uncertainty due to EPS weather forecast up to 100 days ahead and climatology is presented as probabilistic forecasts with 50, 90, and 100% bands.

operations in crisis situations, decide which measures to take.

The end user assessment covered a wide range of issues, including

- Comments on the results of the general and specific questionnaires,
- Analysis of the 'fit-to-purpose' aspects of the service,
- Assessment of how the forecasts could be integrated into the end users' current practices,
- Evaluation of the positive and negative points of the delivered services,
- Identification of potential improvements.

There was a realization that flood forecasts need to be improved concerning all their characteristics (accuracy in amplitude and timing, forecast time, timeliness, persistence, frequency of updating, uncertainties, and so on). Making people aware of uncertainties plays an important role for the users.

As a consequence of the 2005 Danube flood, the Bavarian flood forecasting centers were directed to provide uncertainties with flood forecasts and to implement it into the Bavarian flood information system. This was implemented using an ensemble flood forecasting services (ESFFS). In the process, the design of the representation of uncertainties had to take into account the different interests of each of the different user groups.

Civil protection authorities need a clear statement of what can be expected in the near future (few hours up to half a day). Certain water levels require predefined flood protection measures and corresponding lead times. Only a small bandwidth of uncertainty is tolerable. In Bavaria, flood protection measures are usually operated by the local fire brigades. As most of the staff of the fire brigades in Bavaria are volunteers, an additional (forecast) scenario of what will happen for a few days ahead is also required for better planning of resources.

Flood forecasting centers usually have access to the output of several numerical weather prediction systems (NWPs) which are used as input for flood forecast models. The outputs of different NWPs often show a wide spread. The task is (1) to find out which NWP output is suited best and should be used as input for the flood forecasting models and (2) to estimate by which chance a certain water level will occur. A proper way to obtain such information is to use NWP ensembles. In an NWP ensemble, all members are of equal probability. By statistical means, the most probable forecast and a bandwidth of uncertainty can be obtained from ensemble predictions, ideally with 50 or more members. The flood forecasting centers in Bavaria are not able to operationally run their flood forecast models with this high number of different NWP outputs. A preselection of appropriate weather scenarios as realized in the COSMO-LEPS ensemble (16 preselected members) used in the ESFFS service has proven to be appropriate.

The water management authorities assist other groups. For instance, for reservoir operation, longer forecasts are needed to take maximum effect of the retention storage. In addition, flood warnings require flood forecasts of a certain minimum lead time. On the other hand, longer forecasts increase the risk of false alarms. Probabilistic forecasts that are part of this service are expected to mitigate this problem. Water management authorities have full access to the flood forecasts over the whole forecast period via *intra*net and a special software tool. Depending on the forecast time and the weather situation, the bandwidth of uncertainty can become very wide. If necessary,

Anyname Region	Forecast at 21/09/2009				
Ensemble member	21/09	22/09	23/09	24/09	25/09
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
Discharge ≥ warning level 1	0	0	1	6	13
Discharge ≥ warning level 2	0	0	1	3	8
Discharge ≥ warning level 3	0	0	0	1	3
Discharge ≥ warning level 4	0	0	0	0	2

Figure 4. Example of PREVIEW display of ensemble information.

different flood forecast scenarios with different degrees of detail are prepared by the flood forecasting centers. Water management authorities and flood forecasting centers have made an agreement to discuss and decide jointly which of these forecasts will be published.

The civil protection authorities and the public have access to flood forecasts of limited forecast lead time via the internet. The forecast lead time published varies from gauge to gauge depending on the reliability of the forecast. If the civil protection authorities need longer flood forecasts, they contact the water management authorities who are able to professionally interpret the longer flood forecasts and the uncertainties involved. Extended flood forecasts which are required by the water management authorities are accessible only by professionals who are trained to deal with the uncertainties. The forecasts published are of reduced time and uncertainty so the civil protection authorities are able to work with it (http://www.hnd.bayern.de).

One example of a communication strategy is the Bavarian flood forecasting center's suggestion of five warning states, green for no alert and four color-coded (yellow, orange, red, purple) warning levels related to depth of flooding. Instead of a spaghetti plot, the results for each of 16 ensembles can be communicated via a color-coded diagram such as Figure 4.

7. Dutch Water Boards' risk forecasting platform

About half of the Netherlands is below sea level and the majority of its inhabitants live there. Flood risk arises both from surges along the coast and also from extreme precipitation events. All excessive amounts of runoff have to be drained eventually to large rivers, like the Meuse and Rhine, to the IJssel Lake and to the North Sea. The opportunities for this depend strongly on the respective river and surge levels. Water management in the Netherlands is organized in 27 water boards. One of their main tasks is to prevent fields and cities from flooding in times of extreme precipitation and if necessary to get rid of excess water as soon as possible. But they also have to maintain a minimal water level even in cases of extreme drought.

In order to warn the water boards in cases of potential threats due to meteorological conditions, a warning system was developed by the Royal Netherlands Meteorological Institute (KNMI) in cooperation with the Union of Water Boards. KNMI is only allowed to issue warnings with respect to extreme conditions; forecasts are not intended to be used for day-to-day operation. The warning system is operational since 2003. Currently, 14 water boards have subscribed to the system. Details are given in Kok *et al*. (2010).

In some applications, the main concern may be the probability of occurrence of a particular event within a certain time window. For instance, the Dutch Water Board Fryslan wants to be warned well in advance if the probability of having 10 mm of precipitation in any 12-h time interval exceeds 25%. But in general, it is not that important to know the probability for specific times in the future but it's more important to know what the probability is that it will happen in a certain time *window*, say, on day 3 or day 4.

An example is given in Figure 5 below (forecast of 9 June for which the 0000 UTC run of EPS is used). Here, the estimated 'instantaneous' exceedance probability of 10 mm/12 h is given by the black line and the probability of having this intensity somewhere in a period of 48 h (the previous 48 h) is given by the green line (Figure 5(a)). The latter probability exceeds the 25% threshold. It is interesting to note that the two probabilities differ by a factor of 3 in

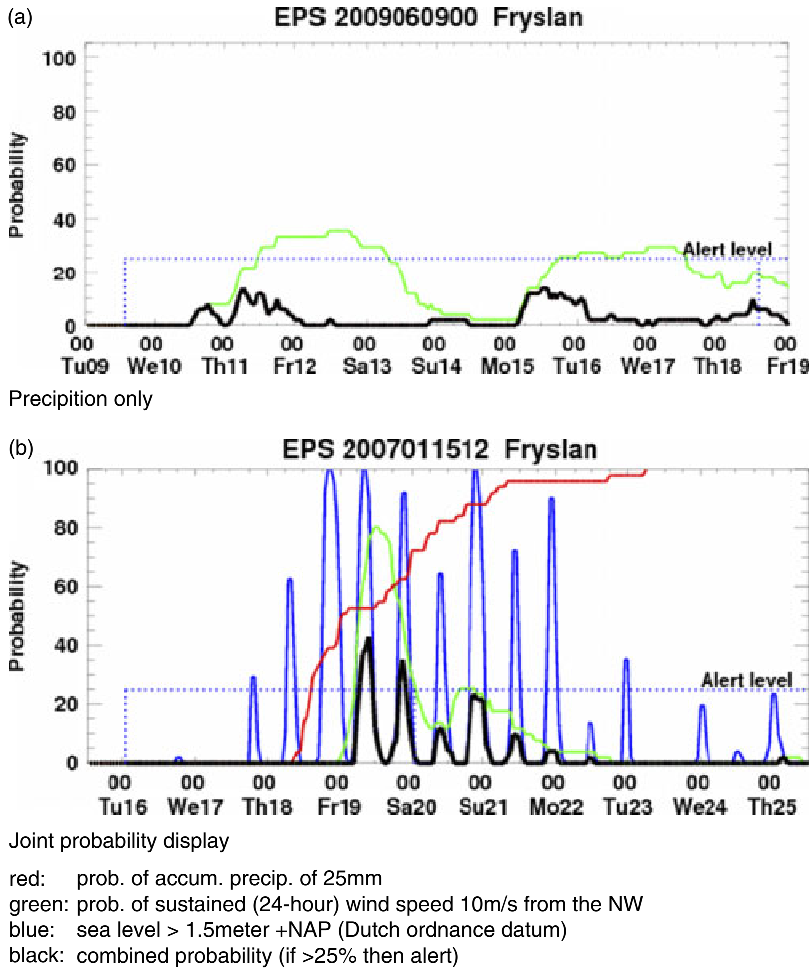

Figure 5. Exceedence probabilities for the Fryslan Water Board, the Netherlands. (a) Precipitation only, (b) joint probabilities. Red: probability of accumulated precipitation of $\geq$25 mm; green: probability of sustained (24 h) wind speed $\geq$10 m/s from the NW; blue: sea level $>$1.5 m + NAP (Dutch ordnance datum); black: combined probability (if $>$25% then alert).

this case. About 40% of the EPS ensemble members agreed on having the intensity in the day 3 to day 4 range but they differ quite substantially on the exact timing of the event, another useful example of how to make better use of the available probabilistic information.

A similar procedure could be used to present simulation information on *combined* probabilities (Figure 5(b)). For the Fryslan Water Board, both wind stress and surge levels determine the amount of water that can be drained to the North Sea. By tailoring the risk conditions more accurately (e.g. by including surge and other meteorological information), the predicted exceedance probabilities can be conveniently linked to the decision models of the user. This will eventually improve the use (and acceptance) and usefulness of uncertainty information.

8. European Flood Alert System platform

There are other European platforms not participating directly in the COST731 Action. Particularly noteworthy is the European Flood Alert System (EFAS) described by Thielen *et al*. (2009). Its decision-support products, developed to deal with uncertain forecasts and to help forecasters in their interpretation, are described by Ramos *et al*. (2007). It grew from a European Union funded research project and now provides flood warnings from 3 to 10 days in advance for large transnational river basins in Europe. It uses weather forecasts from the European Centre for Medium-range Weather Forecasts and from the German Weather Service as inputs to the LISFLOOD distributed hydrological model (De Roo *et al*. 2000) operating at a-5 km grid scale. Warning thresholds, corresponding to the 99, 98, and 97% quantiles were evaluated from a statistical analysis of model simulations. The forecasts are presented in color-coded maps, with the colors determined from the number of ensemble forecasts that exceed an alert threshold. For specific locations, the calculated ensemble hydrographs can be drawn and summarized in color-coded charts. The current formats can be seen at http://efas.jrc.ec.europa.eu/and some examples are illustrated in the Supporting information. Ramos *et al*. (2007) report that users of the system found the combination of deterministic and probabilistic forecasts, included on the charts, very useful and also appreciated the use of color-coded threshold exceedances.

9. Conclusions

As might be expected, given that the subject is at an early state of development, there is not any universally preferred method for communicating uncertainty information to the end user. However, most involve dividing up the forecasted variable and its uncertainty into a small number of probability bands (Sweden, Finland, or EFAS) or warning levels (Germany), usually color-coded and usually chosen by the forecaster and not the end user (except for the Dutch example). Most forecasters are comfortable with providing exceedance probabilities to the end user and these are more likely to be used by the end user if the variable being forecast is the one used directly in their work. Regular meetings between forecast agencies and end users to improve both the calculation of the uncertainties and also how they are presented have proved useful and should improve the use of uncertainty information. The extreme range of time-horizons involved in the examples presented here (months for the Finnish, lake-dominated, example, days for the Swiss examples, and weeks for the Dutch example) illustrates the range of practical situations encountered.

What next? It is clear that our ability to generate uncertainty information in relation to flood forecasts has been matched by the willingness of those responsible for flood management to absorb and consider, at least qualitatively, the information produced. The next challenge is to make use, in a quantitative way, of the probabilistic information in systems to support decision makers.

Supporting information

Supporting information may be found in the online version of this article.

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