A decision support system for effective use of probability forecasts

Simone De Kleermaeker
(i) Deltares, Delft, The Netherlands
(ii) Ministry of Infrastructure and the Environment, Water Management Centre of the Netherlands, Storm Surge Forecasting Service, Lelystad, The Netherlands
simone.dekleermaeker@deltares.nl

Jan Verkade
(i) Deltares, Delft, The Netherlands
(ii) Ministry of Infrastructure and the Environment, Water Management Centre of the Netherlands, River Forecasting Service, Lelystad, The Netherlands
(iii) Delft University of Technology, Delft, The Netherlands
jan.verkade@deltares.nl

ABSTRACT

Often, water management decisions are based on hydrological forecasts, which are affected by inherent uncertainties. It is increasingly common for forecasters to make explicit estimates of these uncertainties. Associated benefits include the decision makers' increased awareness of forecasting uncertainties and the potential for risk-based decision-making. Also, a more strict separation of responsibilities between forecasters and decision maker can be made.

A recent study identified some issues related to the effective use of probability forecasts. These add a dimension to an already multi-dimensional problem, making it increasingly difficult for decision makers to extract relevant information from a forecast. Secondly, while probability forecasts provide a necessary ingredient for risk-based decision making, other ingredients may not be fully known, including estimates of flood damage and costs and effect of damage reducing measures.

Here, we present suggestions for resolving these issues and the integration of those solutions in a prototype decision support system (DSS). A pathway for further development is outlined.

Keywords

Probabilistic forecast, predictive uncertainty, hydrology, decision-making, decision support system.

INTRODUCTION

Hydrologic forecasts are affected by inherent uncertainties, both epistemic and aleatory in nature. It is increasingly common for forecasters to make explicit estimates of aleatory uncertainties, i.e. to produce probabilistic forecasts (Cloke and Pappenberger, 2009). Associated benefits of probabilistic forecasts include the decision makers' increased awareness of forecasting uncertainties and the potential for risk-based decision-making, as described further on in this paper. Also, a more strict separation of responsibilities between forecasters and decision maker can be made. These benefits can only be realised if the decision-response stages of a forecast-decision-response system are designed to take probabilistic forecasts as input, i.e. if the probabilistic forecasts are used *effectively*.

PROBLEM DEFINITION

In the scientific literature, some evidence is shown that using the probabilistic forecasts in risk-based decision making can reduce the users' long-term flood risk, even though these forecasts are unlikely to have 'perfect skill' (Verkade and Werner, 2011; Zhu et al., 2002). However, simply having probabilistic forecasts available is not sufficient to realise the associated benefits. Additional effort is required in areas such as forecast visualisation and communication as well as making effective use of the probability forecast in decision-making processes. Forecasters and decision makers need to work together to develop strategies of how to resolve these issues (Nobert et al., 2010).

As a part of the Dutch government funded Flood Control 2015 program (Stichting Flood Control 2015, 2012), a study was conducted, designed to explore possible methods for making probability forecasts more than a scientific endeavour. From this the following was concluded:

- Some forecast users have a preference for risk-based decision-making as a means to manage the uncertain forecasts. This is useful whether all necessary data is available or not. While probability forecasts provide a necessary ingredient for risk-based decision making, other ingredients may not be present. For example, in many cases no estimates of flood damage, of costs of management measures and of damage reduction are available.
- It is the dimensionality of the probability forecasts, and not the probabilities themselves that make uncertainty forecasts confusing. When moving from deterministic to probability forecasting, a dimension is added to an already multi-dimensional problem; this makes it increasingly difficult for decision makers to extract relevant information from a forecast.

DECISION SUPPORT SYSTEM

While the issues identified above cannot be resolved by means of a Decision Support System alone, such a system may contribute to effective use of probability forecasts. In a sense, the described DSS is a filter that shows only that portion of the multi-dimensional data set that is relevant. The user has to be aware of what information is *not* shown. The described system specifically enables multiple types of users to extract relevant information for their distinct decision-making problems. In that sense, use of the DSS is not limited to specific users or user types. In below sections, ways in which a DSS can contribute to both issues are outlined.

Risk based decision-making

The decision whether or not to implement a risk management measure can be based on the so-called risk approach, which offsets the cost of the risk management measure against the expected value of damage reduction (Krzysztofowicz, 2001; Todini, 2004; Verkade and Werner, 2011). While for many uses one needs to keep in mind that a risk-based approach effectively disregards use of the tails of the predictive distribution, the approach is popular with many users of probability forecasts.

Essentially, in the risk approach two predictive distributions of flood consequences are estimated: one for a situation in which no risk management measures are taken, and one for a situation where measures are implemented. The expected risk reduction attributable to the measures is equal to the difference of expected values of the two distributions. If the expected value of risk reduction is larger than the cost of damage reduction measures, the risk approach suggests that the measure is taken, and vice versa. In the long run, this should minimise the sum of flood related costs and damages.

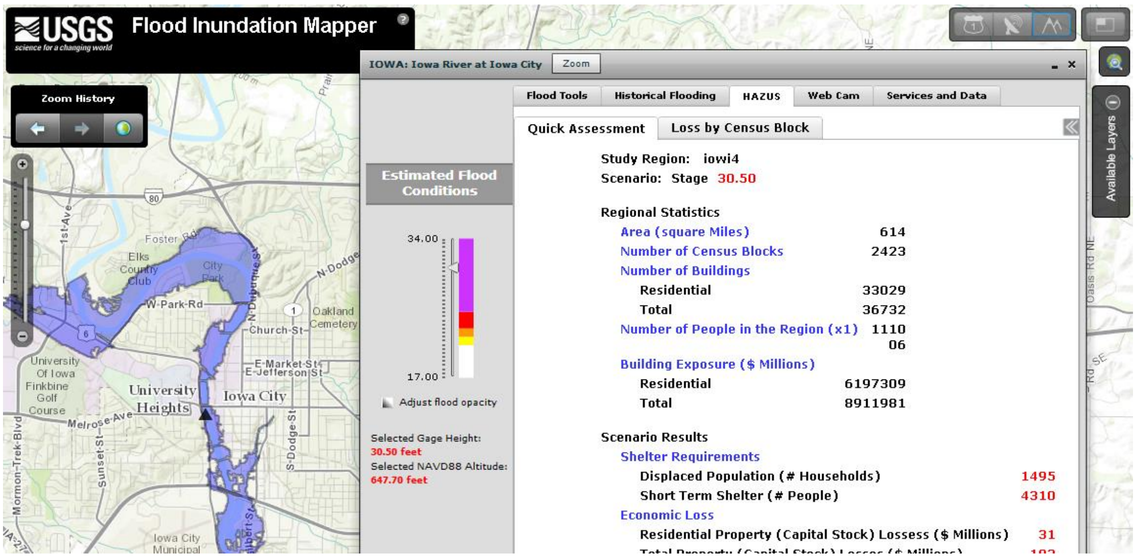

Figure 1: Example of a real-time inundation mapping tool including estimates of flood consequences (source: http://wim.usgs.gov/FIMI/). Such inundation maps constitutes an input to the risk-based decision problem.

This analysis is conceptually easy but is labour and computationally intensive. Making the results of these analyses available during critical situations requires decision support. The DSS prototype allows for a quick analysis of risk by taking the following steps. Inputs to the DSS consist of a real-time predictive distribution of flood hazards and a real-time map of the at-risk area. The system is designed to evaluate flood consequences via inundation mapping at multiple flood hazard levels (Figure 1). This yields a predictive distribution of flood consequences. It is assumed that damage functions are available. These should be prepared off-line, e.g. in the preparation phase of the flood risk management cycle. Likewise, cost estimates of available risk management measures will have to be prepared for use in the system.

Dimensionality problem

For forecasting services that often supply forecast information for long stretches of rivers or coastlines, it is impractical if not impossible to supply forecasts that provide the solution to all users' individual decision-making problems. A probabilistic flood forecast is highly dimensional (time, x- and y-locations, variate, probability) and cannot be fully visualised using two-dimensional graphics, making it it difficult for the untrained forecast user to extract information required to solve her decision-making problem. This "dimensionality problem" is conceptually easy to resolve, but requires somewhat advanced data analysis skills, as well as some knowledge of probability theory and/or statistics. We pose that decision-support may alleviate this problem, by allowing for "viewing" the highly dimensional forecast data in such a way that it directly answers questions posed by the forecast users. The problem is then reduced to Asking the Right Question; this problem is reasonably easy to address.

The DSS prototype is directly linked to the hydrologic forecasting system. The DSS can extract information from the highly dimensional forecast and visualise as per the user's request. For example, from a predictive distribution of water levels, the system will extract the probability of exceedence of a certain water level (Figure 2). It thus answers a forecast user's question such as: "What is the probability that this road will be flooded by at least 5 inches by 8am tomorrow morning?"

Likewise, other types of forecast visualisations are possible: time series for a certain location (Figure 4a), event probabilities plotted on a map (Figure 3), inundation depths for a certain percentile of the predictive distribution (Figure 4b) are but some of the possibilities. Other options, useful for inland navigation, include minimum water level associated with a certain percentile, along a river stretch.

Essentially, the solution to the dimensionality issue requires that some choices are made as to what aspects of the forecast are plotted. These choices have to be made specific, and have to be clear to the forecast user.

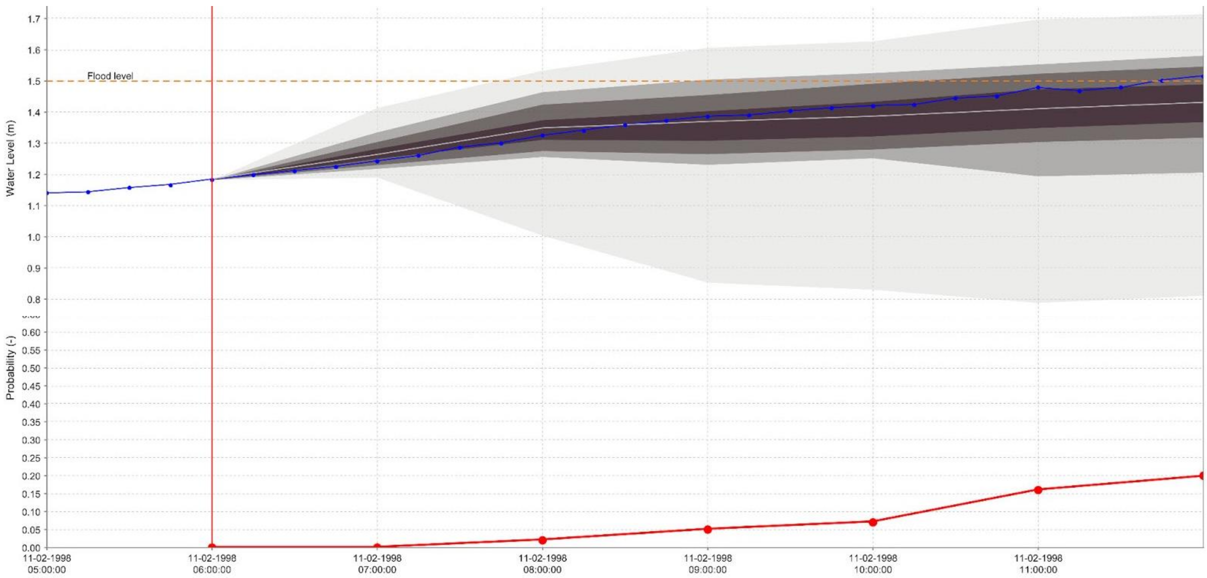

Figure 2: Time series-type visualisation: (top) Discretised probability distribution as function of time; (bottom) probability of exceedence of a critical water level as a function of time. This visualisation is produced within a prototype configuration of FEWS Scotland, which is built using the Delft-FEWS production system (Werner et al., 2012).

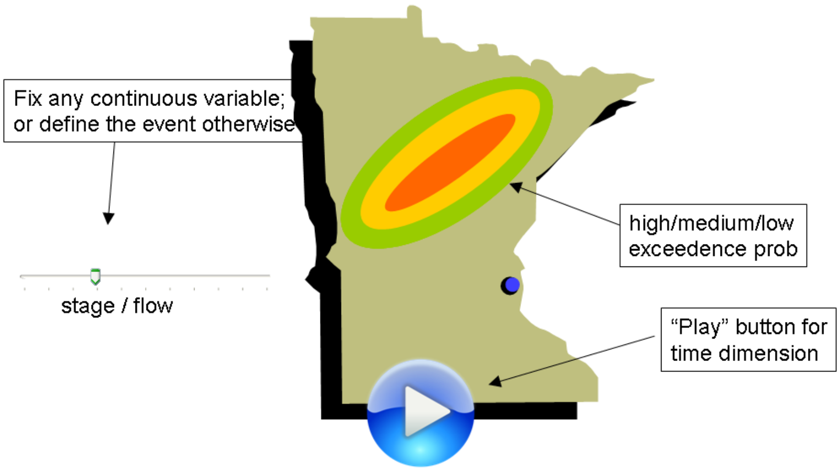

Figure 3: map-type visualization of event probabilities, as a function of time

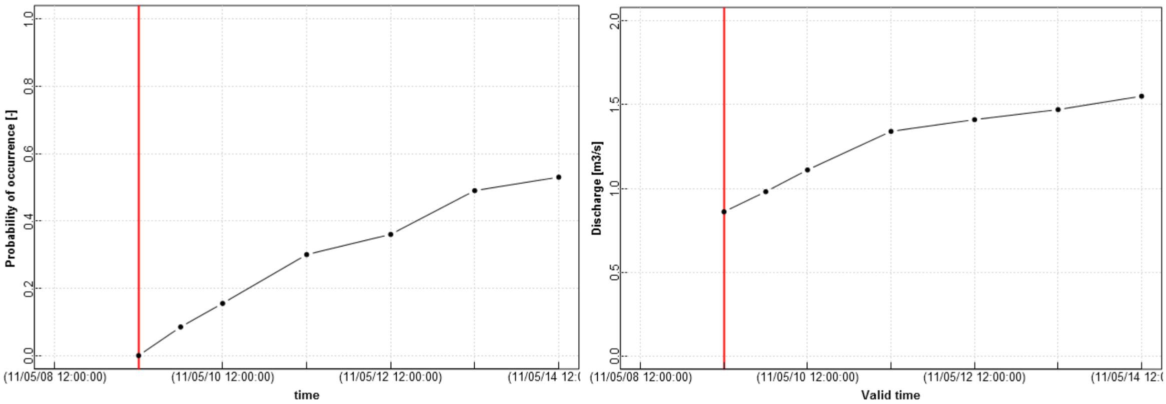

Figure 4a: Time series-type visualisation: (left) for a fixed location and event it shows the probability in time; (right) for a fixed location and probability it shows the river discharge in time. These visualisations are off-line prototypes, based on typical visualisations that would be made within the Delft-FEWS forecast production system.

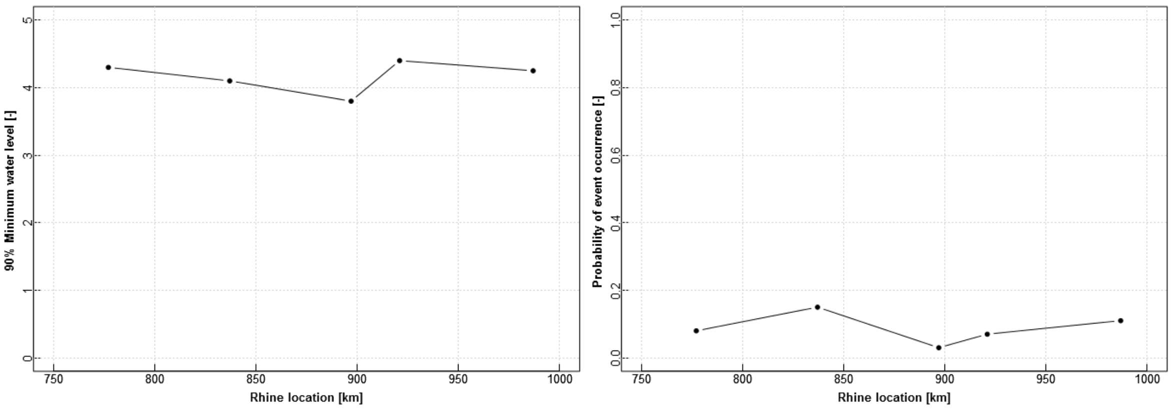

Figure 4b: Time series-type visualization: (left) for fixed time and probability (90% percentile) it shows the minimum water level along the river; (right) for fixed time and water level it shows the probability along the river.

PROJECTED DEVELOPMENT OF THE DSS

First steps towards operationalizing the described DSS were made within the Flood Control 2015 program. As a first step, an ensemble streamflow forecasts was used to estimate a predictive distribution of streamflow. Subsequently, this distribution was combined with a damage function to estimate a predictive distribution of flood damage, from which real-time flood risk was estimated (Verkade and Vreugdenhil, 2012). Supplying this information to an end user constitutes a useful form of decision support.

The DSS will be further implemented for two distinctly different regions within The Netherlands: the floodplains of the Meuse River, and the polders bordering Lake IJssel. This allows us to apply the DSS in two very different ways.

- For the Meuse River Maas the threat comes from the river stage. Flood plain inundation occurs relatively frequently (once every 2 to 5 years). While resulting damage is limited, action is required however to evacuate livestock and close access roads.
- For Lake IJssel the combination of water level and waves at the lake can cause overtopping of the dikes or a levee breach. This would result in inundation of the inland polders. For this hydrodynamic system, the probability of load (i.e. water level forecast) is combined with the probability of levee breach (i.e. dike stability) into one probability of failure, from which we infer the risk function. The damage function for this system is very steep, so the stakes are high. However, this particular hydrodynamic system has a relatively infrequent need for decisions.

To the best of the authors' knowledge, no similar Decision Support System exist within operational real-time forecast – decision – response systems that are used for flood warning and response. While the described DSS will be designed specifically for application within hydrologic forecasting systems, we hypothesise that the methodology can be useful within other applications as well.

ACKNOWLEDGMENTS

The work underlying this paper has been partly financed by the Flood Control 2015 research program, a collaboration between the Dutch government, non-government organisations and the private sector.

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