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Methods and tools to support real time risk-based flood forecasting - a UK pilot application

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Abstract. Flood managers have traditionally used probabilistic models to assess potential flood risk for strategic planning and non-operational applications. Computational restrictions on data volumes and simulation times have meant that information on the risk of flooding has not been available for operational flood forecasting purposes. In practice, however, the operational flood manager has probabilistic questions to answer, which are not completely supported by the outputs of traditional, deterministic flood forecasting systems. In a collaborative approach, HR Wallingford and Deltares have developed methods, tools and techniques to extend existing flood forecasting systems with elements of strategic flood risk analysis, including probabilistic failure analysis, two dimensional flood spreading simulation and the analysis of flood impacts and consequences. This paper presents the results of the application of these new operational flood risk management tools to a pilot catchment in the UK. It discusses the problems of performing probabilistic flood risk assessment in real time and how these have been addressed in this study. It also describes the challenges of the communication of risk to operational flood managers and to the general public, and how these new methods and tools can provide risk-based supporting evidence to assist with this process.

1 Introduction

Effective flood forecasting has the potential to save significant numbers of human lives, as well as saving disruption to many times that figure. The latest data puts the size of historical flood disasters into context, illustrated clearly through information on the impacts of the top ten flood disasters globally since 1900, through the numbers of people killed, and economic damage (where known) (Table 1), and the equivalent data for Europe (Table 2). The striking feature of these statistics is that in the first half of the twentieth century, hundreds of thousands of people lost their lives to flood disasters, particularly in Asia. All significant flood events have huge economic impacts, too. This highlights the importance of improving flood warning and operational flood risk management, as well as ongoing work towards the 'reduction of the adverse consequences for human health, the environment, cultural heritage and economic activity associated with floods in the Community', specified in Article 1 of the EU Floods Directive.

Country	Date	Number killed	Total damage ('000 US$)
China	1931	3,700,000	1,400,000
China	1959	2,000,000	-
China	1939	500,000	-
China	1935	142,000	-
China	1911	100,000	-
China	1949	57,000	-
Guatemala	1949	40,000	15,000
China	1954	32,000	-
Venezuela	1999	30,000	3,160,000
Bangladesh	1974	28,700	579,200

Table 1. Top 10 most important global flood disasters for the period 1900 to 2015 sorted by numbers of people killed at the country level.
Source: EM-DAT: The OFDA/CRED International Disaster Database [1]

Country	Date	Number killed	Total damage ('000 US$)
Netherlands	1953	2000	300,000
Romania	1926	1000	-
Spain	1973	500	400,000

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Portugal	1967	462	3000
Spain	1962	445	80,000
Italy	1985	329	15,000
Hungary	1970	300	85,000
Russian Federation	2002	259	1,007,970
Romania	1970	215	500,000
Russian Federation	2012	179	617,000

Table 2. Top 10 most important European flood disasters for the period 1900 to 2015 sorted by numbers of people killed at the country level.
Source: EM-DAT: The OFDA/CRED International Disaster Database [1]

The drivers for more effective flood forecasting and warning systems are clear, to support informed decision making and minimise the residual risk for flood defences. The contribution of flood risk to the average annual loss on a global level is estimated at US$104 billion [2]. The countries with the highest average annual losses due to flooding are China, the United States of America and India. Therefore, 'even a small percentage reduction in losses through better early warning will translate into very significant savings, not to mention the benefits of avoiding disruptions of households and businesses and most importantly the saving of lives'. An Australian study [3] stated that the cost-benefit ratio for urban flood warning systems is 'extremely favourable', and that investment in urban flood warning systems is likely to be the most cost-effective flood mitigation strategy.

This paper presents a collaboration that is developing tools and techniques to extend existing flood forecasting systems with elements of strategic flood risk analysis, including probabilistic failure analysis, two dimensional flood spreading simulation and the analysis of flood impacts and consequences. In this way, these tools will offer new information to flood forecasters and warning teams, to assist with more effective emergency response.

1.1 Current practices in flood forecasting

Currently, the production of model-based deterministic forecasts of discharge or water levels in rivers is common practice for flood forecasting systems. In recent years, such deterministic model-based flood forecasting systems have been established all over the world for different spatial scales. Examples are: the Global Flood Awareness System (GloFAS) [4] and Global Flood Forecasting and Information System (GLOFFIS) [5] on a global scale; the European Flood Alert System [6] on a continental scale; the flood forecasting system of England, Scotland and Wales [7] on a national scale; and the forecasting system for the Salado Creek in Texas [8] on a basin scale. Further examples are provided in [9, 10]. In general, these model-based forecasting systems include a process chain (Figure 1) which starts with a meteorological model for each sub-catchment that predicts the amount and spatial distribution of precipitation, and, if relevant, wind and temperature fields, over time. This is typically followed by a hydrological model of each sub-catchment, which converts the meteorological data into hydrological data, such as discharge at the sub-catchment outlet. In some cases, there is a further step in the process chain, wherein the sub-catchment discharges are used as boundary conditions for a hydrodynamic model, giving water levels and flows along the main reach of interest. The model chain can be run in deterministic mode, using a single weather forecast as main input, or in probabilistic mode, where an ensemble weather forecast represents the uncertainty in the meteorological input, which is typically the main source of uncertainty for longer lead times. A key factor in setting up this process chain is the length of time taken from real time measurement in the catchment, through to flood warning. As part of the chain, suitable thresholds upon which to base flood warnings are used as a post-process, to provide a fast way to analyse results and present key information to the operational flood manager.

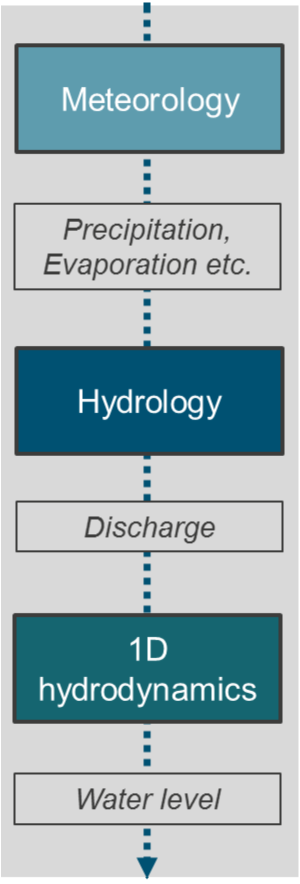

Figure 1. Current process chain for model–based flood forecasting: from meteorological forecast to a water level forecast.

In parallel with this operational context, flood risk managers use event-based tools to calculate flood risk. Advanced hydrodynamic models can translate the water level in the river to defence overflow or breaching and 2D flow over the hinterland based on a Digital Terrain Model (DTM). These models provide geographical flood maps of inundation extents, water depths and associated likelihoods. This information has typically been available for strategic planning, i.e. not in an operational context. Computational restrictions have prevented the flood risk information from being available for operational purposes. Those restrictions have primarily been related to the vast amount of data that are need for 2D flood mapping, and the lengthy simulation times

In practice, the operational flood manager has questions to answer, which are not completely supported by the outputs of traditional flood forecasting systems. The types of questions that require answers within an emergency response framework, are:

- Where and when is a failure of my flood defence system possible?
- Where and when should I reinforce my flood defence system?
- What are the consequences and impacts of an overflow or a breach?
- Which areas should I evacuate first and how can I evacuate them most effectively?
- What is the accuracy of the flood forecast?

Currently, these questions are answered based on expert knowledge and/or pre-calculated information (e.g. about defence performance or flood spreading behaviour in the area) which is available in the responsible emergency response organisations. One example is the FLIWAS-platform [11], which is applied in Germany and the Netherlands. It uses pre-calculated flood maps to support the planning of emergency measures. A similar approach is applied in the web-based LIZARD platform, used in the Mekong delta for example, providing a database with pre-calculated flood scenarios [12].

Increasingly there is a need for flood risk and consequence information to become available in real time. As flood risk analysis is becoming advanced and widely used, the flood forecasting community increasingly uses the pre-calculated data as part of their decision-making process. The use of these outputs, an increase in data availability and computational resources is currently leading to a shift in operational flood forecasting towards geographical and probabilistic flood risk information.

Several research studies have been carried out in this field. One example is the application of an extended flood forecasting system for the Mittlere Elbe in Germany, including meteorological, hydrological, and hydrodynamic models combined with a deterministic assessment of the defence performance [13]. Another example is the EU-funded project UrbanFlood [14, 15], which analysed and tested an extended process chain for flood forecasting by defence failure, breaching and flood spreading models. The Distributed Research Infrastructure in Hydro-Meteorology (DRIHM) project combines data and models from across the expertise of Europe to exhibit how these components can be combined in an integrated modelling chain to better improve our predictions of extreme events, demonstrated through application to simulate the extreme hydro-meteorological event that occurred in Liguria, Northern Italy in November 2011. The surface water flood risk forecasting system in Glasgow for the Commonwealth Games of 2014 [16] included the potential impacts of surface water flooding on people, property and transport as real time outputs. A very recent study applied flood forecasting and Inundation mapping using HiResFlood-UCI and Near-Real-Time Satellite Precipitation Data for the 2008 flood in Iowa. This study does not only apply innovative sources of data, but also outputs a probabilistic inundation prediction [17]. These approaches have demonstrated opportunities in probabilistic flood risk analysis in operational forecasting, but have also shown limitations; specifically, the computational load and large datasets limit the number of ensemble simulations that can be carried out. Furthermore, consideration needs to be given to the methods of conveying information on uncertainty to end users, so that they can make effective decisions based upon probabilistic outputs.

To enable further progress, a software toolkit was developed based on Delft-FEWS to support probabilistic risk assessment in an operational context, so that the techniques can be more widely applied and tested.

1.2 Flood forecasting using Delft-FEWS

Delft-FEWS is a generic forecasting system that manages data and models in a real-time environment [18]. It provides a shell within which an operational forecasting application can be developed specific to the requirements of an operational forecasting centre [19]. This has been used for several operational forecasting systems, such as for the Rhine basin in Switzerland, and systems across England, Wales and Scotland [18]. One of the major strengths of Delft-FEWS is the flexible nature of the software which allows the integration of a large range of models and data. Delft-FEWS accommodates the process chain of models traditionally used in flood forecasting, and new modelling tools can be easily adapted to run inside this process chain. Figure 2 shows how this chain of models fits into the Delft-FEWS software.

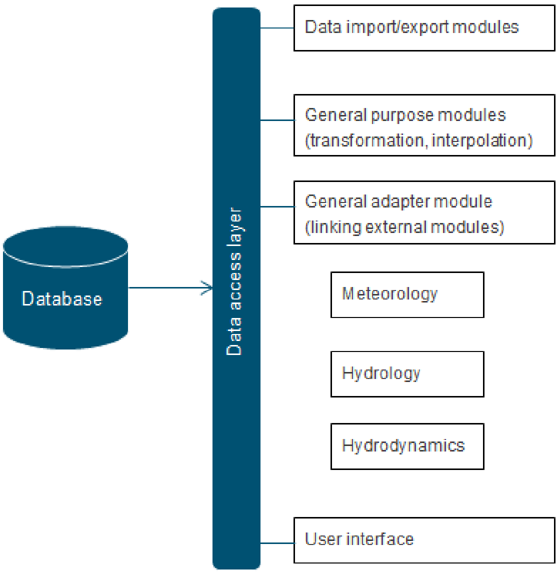

Figure 2. Overview of the Delft-FEWS modelling platform as applied in flood forecasting.

In the Delft-FEWS software, the hydrology and hydrodynamic models are usually setup as external modules. This means that existing models from flood risk analysis or existing operational flood forecasting systems can be used inside this framework. The external models interact with the FEWS-database using an adaptor. Currently there are adaptors available for 75 types of model. Examples of some widely used models are the PDM model, HEC-RAS, SOBEK, ISIS and JFlow. These are all examples of hydrological and hydraulic models, but the flexible nature of the Delft-FEWS setup means that different types of external models can easily be added to the traditional process chain of flood forecasting. This offers the opportunity of expanding the traditional chain of flood forecasting models with risk and impact models, without needing to do any major re-structuring of the forecasting system.

1.3 The next step forward for flood forecasting systems

This paper outlines a collaboration between HR Wallingford and Deltares, which has as its aim the provision of tools to enable probabilistic forecasts that support the decision maker with additional information to support emergency responses. The operational concept presented here is based on extending the currently applied forecast process chain (represented in Figure 1) using modelling techniques already applied and combined for several years in the field of strategic flood risk assessment. These methods are:

- probabilistic failure analysis;
- two dimensional flood spreading simulation;
- breach modelling; and
- analysis of flood impacts and consequences.

In this way, additional model-based forecasting information is provided to the decision maker within an emergency response organisation, such as:

- Location, timing and probability of failure of defined sections of the flood defence line;
- Flood spreading, extent and hydraulic values in the protected area caused by an overflow or a breach flow;
- Impacts and consequences of flooding in the protected areas, such as injuries or casualties and/or damage to critical infrastructure or economy.

The additional model-based forecasting information supports the design of emergency measures (e.g. location, time, and type) and can increase their lead time. Moreover, the decision maker gets a broader overview of the prospective situation than is currently possible using deterministic forecasts. It is important to mention that this information should not replace the expert knowledge; the idea is to extend the already available information.

The paper gives a description of the three aspects of additional model-based forecasting information given above, and the tools that have been developed to provide this information, as extensions to the traditional process chain. These are being integrated into the Delft-FEWS software system as shown in Figure 3. The value of the newly generated information in decision support for emergency response during a flood event is highlighted and discussed.

2 Integration of risk-based tools for operational risk forecasting

The extended process chain (Figure 3) offers several tools from which the user can choose to address a specific need for information; these are: a probabilistic defence breach module, a 2D hydrodynamic flood model and a flood impact module, It is likely that the user will not need to use all model components for a specific application. Typically, the basic process chain of Figure 1 stays the same, as do the underlying models, but with some new options available depending on the needs of the user.

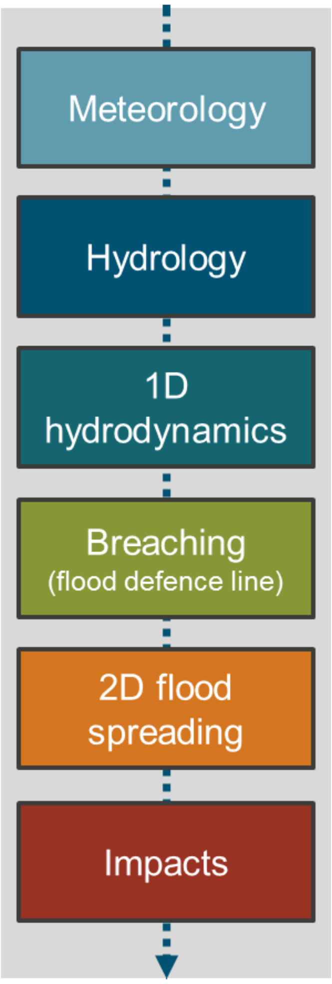

Figure 3. New process chain for probabilistic forecasts, from meteorological forecasts to impacts information.

Should the user be interested in flood defence assessment, then two new tools are available, which are run following the hydraulic model of the river to simulate the breaching process. Probabilistic failure analysis calculates the structural reliability of the defence, which can then be combined with breach analysis to simulate the failure of the defence. These are described in detail, with case study applications in [20]. The spreading of the flood water across the flood plain can then be calculated, which then enables the assessment of likely impacts and consequences to be carried out.

The chain is driven by ensemble rainfall forecasts, which are the best estimates of forecasted rainfall given uncertainties in the observations and starting conditions. By sampling the uncertainty in the starting conditions, and running several ensemble members forward with the weather forecast model, meteorologists arrive at an estimate of the rainfall forecast uncertainty. By running a set of representative ensemble members through the operational flood forecasting process chain, we gain the added value of an understanding of the risk of flooding in real time. The modelling components are described in more detail in the next section.

The essence of operational risk forecasting is timely delivery of accurate information. The judicious selection of component models for these processes is therefore important, to ensure that they are able to run very fast, allowing time to perform multiple simulations driven by samples from ensemble rainfall forecast scenario inputs.

2.1 Probabilistic failure analysis

The fragility curve $Frc(h_w)$ expresses the reliability of a structure as a function of a defined dominant stress variable [21]. In this context, the water level at the structure is defined as the dominant stress variable. The fragility curve shows the conditional probability of the occurrence of a failure event $P(failure|h_w)$ on the vertical axis as a function of the water level h_w, represented on the horizontal axis (see Figure 4).

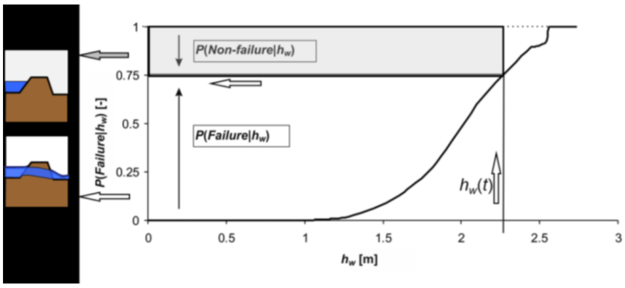

Figure 4. Concept of the fragility curve and the transformation from water level h_w to probability of failure $P(failure|h_w)$

The concept of the fragility curve was developed as part of the reliability analysis of engineering structures (e.g. [22]). According to [23], the application of fragility curves in flood management systems dates back to 1991. Since that time further developments in the methods of determining fragility curves (e.g. [24]), the intrinsic level of detail (e.g. [25]) and their integration into flood risk assessment models [26; 27] have been researched. Various research projects concerning flood risk assessment have included the concept of the fragility curve (e.g. [28]).

However, the application of fragility curves focusses mainly upon strategic flood risk assessment and the planning of flood protection measures. Trends show an increase in the application of fragility curves for assessing operational reliability [23]. For example, [29] uses pre-calculated fragility curves for 60 defence sections of the Emscher river to include also probabilistic aspects of defence failure into an operational flood forecast.

2.2 Breaching of flood defences

The risk approach requires a rapid and accurate method of assessing the impact of a possible flood event on a given system of flood protection. One part of that process is the prediction of a flood volume through an embankment breach. AREBA (A Rapid Embankment Breach Assessment) simulates the process of breaching within embankments. It incorporates the effects of a grass cover on the flood hydrograph shape, and calculates a flood hydrograph for surface erosion, headcut erosion or piping failures.

AREBA has been successfully benchmarked against other breaching models and also validated full scale and laboratory physical model experiments (EU-IMPACT and USDA-ARS). AREBA is exceptionally computationally efficient and has been designed specifically for use in probabilistic flood risk analysis models that require the impact of multiple breach scenarios to be evaluated [30].

2.3 Two dimensional flood spreading simulation

Flood inundation mapping in urban areas is becoming increasingly important, in order to provide information on the areas adjacent to the river that are likely to flood, and to present that information in a map format that is easy to understand. Two-dimensional (2D) computational hydraulic models are normally used to predict how floods propagate and to provide details of flood depths, durations and velocities. The use of traditional 2D flood models in urban areas, where a high spatial resolution is required, can result in long run-times. The new toolkit is therefore based upon new inundation model software RFSM-EDA (Rapid Flood Spreading Model: Explicit Diffusion waves with Acceleration) that uses a unique sub-grid meshing system. RFSM-EDA is orders of magnitude faster than a traditional 2D hydraulic model [31, 32], and has adopted the Rapid Flood Spreading Model with Explicit Diffusion wave with Acceleration terms (RFSM-EDA). The RFSM-EDA model has previously been adopted for strategic flood risk planning proposes and has the capability to be used to run tens of thousands of different scenarios. For the purposes of probabilistic flood forecasting, the fast run times mean that it can be added to the chain of models run in real time without having a notable impact on the overall run time of the operational system. This model can be applied at a catchment, regional, national or continental scale. In terms of accuracy, the RFSM-EDA has been shown to reproduce the behaviour of traditional 2D models in a number of independent benchmark tests prescribed by the Environment Agency in the UK [33]. The speed of RFSM-EDA is due to the fact that it maximises the benefit of the sub-element representation while undertaking the computations on a coarse grid.

Here, the RFSM-EDA has been added to the Delft-FEWS toolkit. In a typical flood forecasting model set-up, a 1D river model is used to calculate a time series of water levels in the main reach of the river. Incorporating the 2D RFSM-EDA, provides the facility for water to spill from the river into the flood plain and this inundation process is carried out through linking the 1D river model and the 2D inundation model (RFSM-EDA).

2.4 Analysis of flood impacts and consequences

In order to help the emergency responder to answer the question ‘what are the consequences and impacts of an overflow or a breach?’, it is necessary to extend the probabilistic flood analysis to combine the forecasted flooding with information on the people and assets that lie in those flooded areas.

This study adopts tools that have been developed and used in a planning context to estimate the impact of flooding on buildings, agricultural land and people. These tools have been combined into an Impacts Calculator, to enable a more integrated evaluation of the impact of flooding. The Impacts Calculator has been integrated as the final stage of the flood forecasting model chain within Delft-FEWS. The intention is that this feature will enable provision of operational information to emergency responders on potential impacts and consequences.

The Impacts Calculator first calculates the damage in each grid cell of the flood area, using the cell water depth (usually the maximum depth) by interpolating a depth-damage curve. Objects that may be subject to damage are assigned to cells on the grid. The damage for each object or for each damage category (residential, agricultural, a given district etc.) can then be calculated for a set of depth values. The grid, depth-damage curve and damageable object definitions are specified using an XML file.

The subsequent Loss of Life calculation is based on the Risk To People method [34]. Various properties of the area to be flooded can be considered: presence of a warning system, nature of the buildings, proportion of more vulnerable people (elderly people, less-able or sick people). The tool is flexible and can be run with minimum data, however this will influence the quality of the results. The inundation is characterised by a speed of onset coefficient and by a hazard grid (function of flow depth, speed and debris factor, usually calculated by a hydraulic model). The original method is applied on a grid to derive a spatial map of the predicted loss of life.

This is a simplified method that does not consider explicitly the evacuation of people or the evolution in time of the inundation and the changing location of people. More complex models exist, but this approach was chosen for this application because of its simplicity and low computational cost.

3 Case study application

These new operational flood risk management tools are currently being applied to a pilot catchment in the UK, which has a particular focus on the need for timely flood maps and impacts information to support emergency responders. The River Nith catchment covers the town of Dumfries, Scotland. Dumfries is a SEPA Target Area, having suffered from significant, disruptive flood events affecting large numbers of inhabitants, most recently during winter 2015-16. SEPA are therefore interested in gaining a better understanding of the flood risk and impacts in real time for this catchment.

In addition to testing the modelling strategy through this case study, methods of conveying results are being tested. Map based results may include such information as the gridded presentation of water level probabilities and/or numbers of affected people.

4 Discussion and conclusions

Flood risk tools have been adapted to run inside Delft-FEWS. The performance of the tools is being tested and demonstrated via catchment pilot studies, so that the benefits to end users can be realised and maximised. The system will need to rapidly provide real-time risk information, meaning that all the additional components must have minimal computation time and the number of ensembles should be limited, but still give statistically sound results.

The communication of uncertainty requires special consideration, to ensure that all stakeholders receive information that is understandable and beneficial. The type of information that it is appropriate to provide depends upon the end users; the general public is becoming increasingly familiar with uncertainty information in some countries, where weather forecasts are presented in this way. The Flemish Environment Agency’s website displays both short-term forecasts and long-term probabilistic forecasts, having 10-days’ lead time, based upon ECMWF-EPS percentiles (10th, 25th, 75th, and 90th) [35]. This means that an envelope of four time series can be presented to end users, covering the full range of possibilities, with guidance being simply ‘the wider the band, i.e. the further the forecasts are from each other, the greater the uncertainty’. Similar graphs and guidance are used by the Dutch national weather service (KNMI) for their maximum temperature forecasts. The National Weather Service in the United States graphs the weekly chance of exceeding key water level, stage or volume thresholds, grouping the exceedance into bands of around 25%, based upon the total range of past data, with accompanying guidance stressing that these figures are indicative and that conditions are expected to change. Emergency responders may need to assimilate uncertainty information in such a way that they can quickly make a suitable decision on the action needed, without confusion caused by additional risk statistics.

Feedback from users is being gathered throughout the course of the pilot studies, to help tailor the outputs to their needs. It is possible that these tools will have application for training procedures as well as in operational situations.

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