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Flood probability mapping by means of conceptual modeling

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ABSTRACT: Flood forecasting systems which provide real time flood maps are a valuable source of information for water managers and emergency units in case of flood events. However, the uncertainty involved in the flood forecasting and its influence on the inundation results and flood maps is most often not taken into account. This paper presents a method which allows producing probabilistic flood maps. These flood maps show the probability of flooding for areas in the vicinity of the modelled river. They can be updated in real time based on rainfall forecasts and related updates in the flood forecast.

The approach was tested for the Dender river in Belgium for the flood of November 2010. It is shown that the probabilistic flood maps can provide accurate predictions of the flood probability. The method was validated based on historical data on the flood extent.

1 INTRODUCTION

River flood forecasting systems become widely used for real time prediction of runoff and river discharges, river water levels and inundation variables along floodplains. When these systems are linked to a GIS interface, flood maps can be produced and updated in real time. These flood maps provide a valuable source of information for water managers and emergency units during flood events. They, however do not provide information on the uncertainty of the predicted inundation levels. The uncertainty in the water levels in the floodplains typically originates from the uncertainty on the input, the model parameters and the model schematization of the flood forecasting system.

In the recent past several methods have been developed to quantify this uncertainty, like the GLUE method by Beven & Binley (1992), the Bayesian Model Averaging by Raftery (1993), the Bayesian Forecast System by Krzystofowicz (1999), the Model Conditional Processor by Todini (2008), the Quantile Regression technique by Weerts et al. (2011) and the Non-parametric Data-based Approach by Van Steenbergen et al. (submitted). Each of these methods are able to quantify the uncertainty in the flood forecasts at gauged locations along modeled river stretches. The listed methods have their advantages and disadvantages, which are discussed in Coccia & Todini (2010) and Van Steenbergen et al. (submitted). In this paper the Non-parametric Data-based Approach has been applied to quantify the uncertainty.

Next to the quantification of the uncertainty in the flood forecasts, also the careful communication and visualization of this uncertainty has to be addressed (Kloprogge et al., 2007). One of the presentation forms are probabilistic flood maps, which show the probability of flooding for areas in the vicinity of the river. This kind of maps could help the emergency units to focus their actions on the areas with the highest flood probability. In addition different flood management strategies could be calculated in real time and the strategy which offers the lowest flood probabilities could be chosen. Given that these flood maps are produced and used during critical periods, the method and software that calculate and map the flood uncertainty have to be robust, with limited calculation time.

2 CASE STUDY

2.1 *Dender*

The Dender is a strongly channelized river controlled by 8 hydraulic gates and sluices (for navigation and flood control). It has a downstream tidal influence from the river Scheldt. The Dender basin has a total area of 1384 km^2 of which 708 km^2 lies in Flanders. The river flow is strongly affected by rainfall over the upstream basin (Figure 1). The Dender has an assymetric valley; the West side is relatively flat, while the East side lies in an indulating landscape with narrow, rather strongly incised river valleys. The dominant soil type is loam. The Dender basin has a high urbanization degree of 30%, concentrated in the North of the basin. The South of the basin is characterized by arable land. Larger historical floods have occurred in 1993, 1995, 1999, 2002 and 2010. Where as the average discharge of the Dender at the upstream gauging station of Overboelare is 5 m^3/s, during the recent flood period of November 2010 the discharge rose to more than 100 m^3/s at this location causing severe floods (Van Steenbergen et al., submitted).

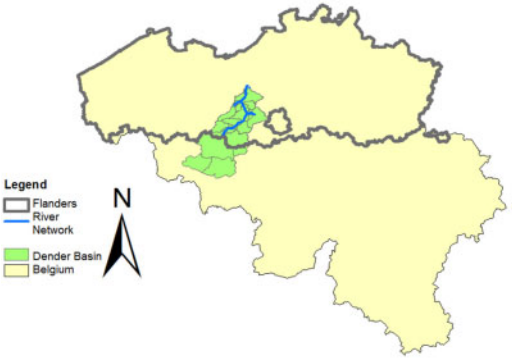

Figure 1. Location of the Dender basin and the river network.

2.2 *Flood forecasting system*

The food forecasting system used in this study is operationally run by Flanders Hydraulics Research and provides forecasts of water levels and discharges on the navigable rivers in the Flanders region of Belgium. The system contains a combination of catchment hydrological and river hydrodynamic models and a data assimilation module for real time updating. The hydrological models are lumped conceptual rainfall-runoff models implemented in the NAM module of the Mike 11 software of DHI Water & Evironment (DHI, 2007a; DHI 2007b; Madsen, 2000). Also the hydrodynamic models are implemented in the Mike 11 river modeling system.

The hydrological models of the gauged basins are calibrated using long term (>5 year) rainfall and evapotranspiration series. The model parameters of the ungauged basins are derived from interpolation between the surrounding gauged basins.

The hydrodynamic model has been calibrated and validated based on recent flood events, making use of available observations of water levels and discharges along the river stretches.

The models are run several times a day. Each simulation period takes four days, consisting of a two day hindcast period and a two day forecast period. The hindcast period allows the data assimilation module to adjust the simulation results with the available observations. The data assimilation does not only create optimal initial conditions, but also allows to adjust the forecast results, based on an extrapolation of the in time correlated errors during the hindcast period.

3 UNCERTAINTY ANALYSIS

Different methodologies can be followed to assess the uncertainty in flood forecasts. In this paper a technique based on statistical analysis of the model error is used. Typical for techniques that are based on the statistical analysis of model error is that they try to deduct a probability density function of model forecast error from explanatory variables, such as measured or forecasted rainfall, historical model error and current forecasts (Montanari & Grossi, 2008).

The used technique is a non-parametric data-based approach, which is described in Van Steenbergen et al. (2011) and Van Steenbergen et al. (submitted).

The technique starts with an uncertainty analysis of the forecast residuals (differences between the forecasts and the observations). The analysis shows that the distribution of hydrological forecast residuals is not Gaussian, skewed and heteroscedastic. Therefore a non parametric technique was proposed, which does not require the choice of an appropriate probability distribution.

The technique starts by dividing the historical forecast residuals in discrete classes based on the forecasted water level and the lead time. One expects that the forecast predictions are less accurate for longer lead times and extreme water levels. For each combination of forecasted water level and lead time the empirical cumulative frequency distribution is derived. From this distribution different quantiles are stored in a so called 'three dimensional error matrix'. The first dimension represents the forecasted water level class, the second dimension the lead time class and the third dimension the quantile value.

Based on a 3D linear interpolation in this error matrix, the discrete probability density function of a forecasted water level, with a certain lead time, can be derived.

This methodology is used in the operational flood forecasting system of Flanders Hydraulics Research and provides confidence intervals of the forecasted water levels and exceedance probabilities of predefined alert and alarm levels at gauged locations.

The disadvantage of this method is that it cannot provide uncertainty estimates at ungauged locations or for the water levels in the floodplains. Therefore, the method has been extended in order to provide flood probability maps, which give an indication of the flood probability in a spatially variable way along the floodplains.

In order to transform the probability density functions of the water levels at the gauged locations to ungauged locations and finally to water levels in the floodplains, relations, derived from a conceptual river model, are used. The next section describes the development of this conceptual river model.

4 CONCEPTUAL MODELLING

In order to produce flood maps, river flood models are indispensable. Software such as DHI's MIKE11, Innovyze's InfoWorks RS and the USEPA's SWMM solve the Saint-Venant equations using numerical algorithms, which provide an accurate solution under different boundary conditions. However, this technique leads to large computational times, which poses problems for applications that require many simulations, like uncertainty analysis and the generation of multiple forecasts. Therefore, a lumped conceptual model of the downstream part of the river Dender is used in this research, starting just upstream the confluence with its main tributary, the river Marke, and ending 52 km further downstream at the mouth in the river Scheldt. The following paragraphs discuss the buildup of the model.

Kundzewicz (1983) states that due to the limited physical basis and lumped spatial nature, conceptual model parameters cannot be directly obtained from field data. Therefore, calibration to a detailed MIKE11 quasi-2D hydrodynamic model was done. This type of model is an extension of the one dimensional approach, in which a one dimensional river branch is linked to floodbranches through link channels and lateral weirs. This approach strongly reduces the computation time, while providing similar results to those obtained using a two dimensional MIKE21 model (Willems et al., 2002). The conceptual model was calibrated and validated using the historical events of January – February 1995 and November 2010, and synthetic runoff events with 25 and 100 year return period, derived by means of an extreme value analysis applied to a long-term time series of rainfall-runoff discharges covering the period 1967-2003. The composite hydrograph method (Vaes et al., 2000) has been applied to derive the synthetic events.

The river network was schematized by a series of nine segments. Based on the continuity equation, a formula describing the flow rate of a linear reservoir at time $t$can be found. During flooding, the interactions with floodplains distort the shape of the hydrograph. To take this into account, the discharge towards the floodplains was deducted from the upstream inflow before applying the transfer function, hence closing the water balance in each reservoir. This methodology provided accurate results for the seven most upstream segments. Alternatively, one can apply a non-linear input transformation. Previous studies (Beven et al., 2009; Lekkas et al., 2001; Romanowicz et al., 2008) have shown that such a transformation is able to describe the flood effects successfully.

The two most downstream reservoirs show tidal influence, resulting in significant backwater effects. At the mouth, three parallel control structures with complex regulation definitions determine the outgoing flow. To calculate the discharge into the river Scheldt, the overflow equations of a gated weir by Evans & von Lany (1983) were applied. InfoWorks RS software uses the same equations (Innovyze, 2011).

In segments characterized by linear routing, rating curves were derived using the discharge downstream each segment to calculate the water levels at each location of interest. The locations of interest are those along the river where flooding will occur first or those that determine the flow. Figure 2 and 3 display the calibration and validation results for the water level in Overboelare. This methodology is not valid for the two most downstream segments, since there is no univocal relationship between the flow and the segment. Therefore, hypsometric curves were used to determine the water levels at each location of interest.

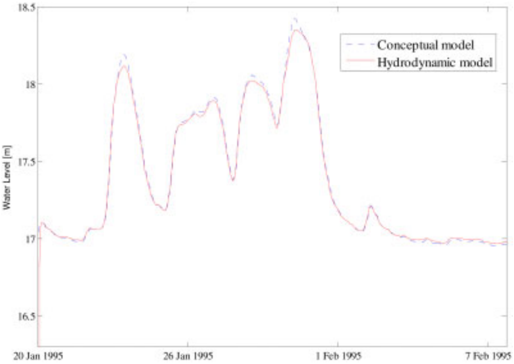

Figure 2. Calibration results of the conceptual model for the water level in the river Dender upstream of the hydraulic regulating structure at Overboelare for the historical event of 1995.

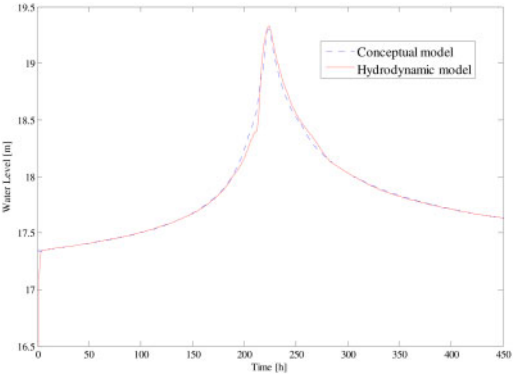

Figure 3. Validation results of the conceptual model for the water level in the river Dender upstream the hydraulic regulating structure at Overboelare for the synthetic runoff event with a 100 year return period.

The dike overflow to the floodplains is conceptually modelled as a flow over a lateral weir, thus following the same approach as the quasi-2D MIKE11 model. The discharge is calculated using the overflow equations mentioned earlier. The floodplains are linked to the river solely at one point, assuming inflow and outflow to occur at the same place. The water level inside the floodplain is determined using a hypsometric curve. Figure 4 shows the validation results of the water level in the left floodplain in the region of Overboelare.

5 FLOOD MAPPING

In a final step the probabilistic flood maps were produced. The relations derived in the conceptual model were used to calculate different quantiles of water levels in the floodplains, based on the quantiles of water levels at the gauged locations along the river. This was done using results of the uncertainty analysis given in section 3. In this study the 2.5, 5, 10, 20, 50, 80, 90, 95 and 97.5% quantiles of water levels were calculated.

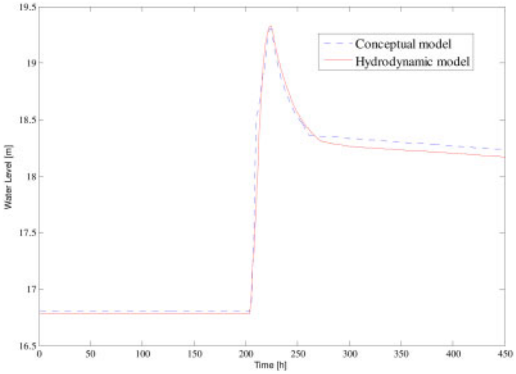

Figure 4. Validation results of the conceptual model for the water level in the left floodplain of the river Dender in the region of Overboelare for the synthetic runoff event with a 100 year return period.

For each of these quantiles, the associated water level in the floodplains was derived. Here the advantage of the conceptual modeling technique becomes clear, because the calculation time to derive these different water levels in the floodplains is very limited (in the range of 1–2 seconds). If the same calculations would have to be made with a hydrodynamic model, the calculation time would be significantly longer and this time is not available in flood crisis situations.

The quantiles of water levels in the floodplain are compared with the surface elevation, derived from the digital terrain model (DTM), making it possible to calculate the flood probability for each pixel (5 m × 5 m) within the floodplain.

6 RESULTS

The method was tested for the flood event of November 2010. The flood probability has been calculated for the flood plains in the region of Overboelare and are shown in Figures 5–7 for different times of forecast.

In Figure 5, a low flood probability is noticeable. Results five hours later show that the flood probability has increased significantly (Figure 6). The increase in flood probability prosecuted, as can be noticed in Figure 7. When the flood probability map of Figure 7 is compared with the observed flood extent of Figure 8, a clear similarity can be observed. The locations with a high flood probability are effectively flooded, which shows the usefulness of the method.

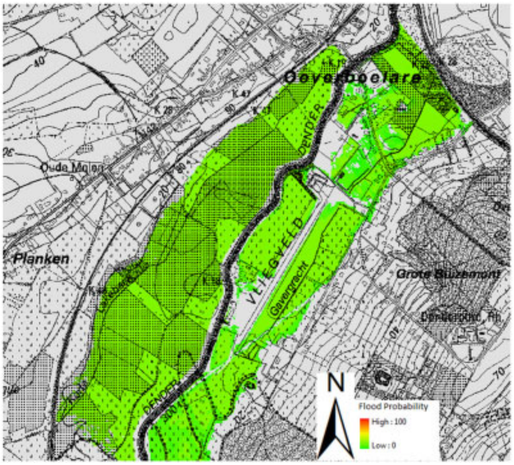

Figure 5. Inundation probability (%) map for the next 48 h for the river Dender at Overboelare on 13 November 2010 05:00.

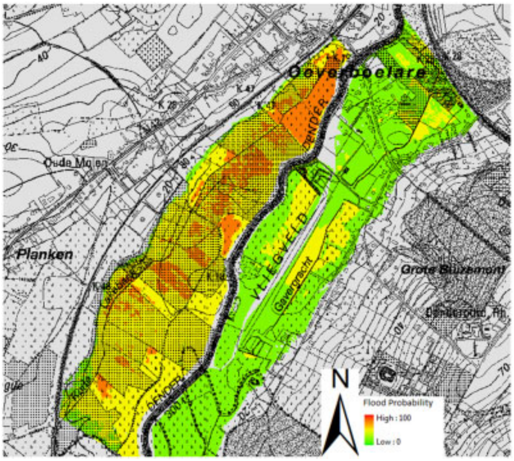

Figure 6. Inundation probability (%) map for the next 48 h for the river Dender at Overboelare on 13 November 2010 10:00.

7 CONCLUSIONS

Uncertainty communication in river flood forecasting becomes more and more important. The method in this paper showed how the uncertainty in the flood forecasts can be visualized in flood probability maps. Essential for this method is the use of a conceptual model, which relates the floodplain inundation levels to the river water levels. Making use of this model, quantiles of water levels can be calculated at different locations along the river, within a very short time frame, allowing a fast production of the probabilistic flood maps.

The method has shown to be very efficient for the flood event of November 2010. The observed extent of the flood matches very well with the extent shown in the flood probability map.

By making use of these flood probability maps in the future, water managers and flood crisis managers could focus their actions on these areas with the highest flood probability. Even if the maps would become available online in real time, people could check the locations of their houses and take proactive measures to reduce the personal damage.

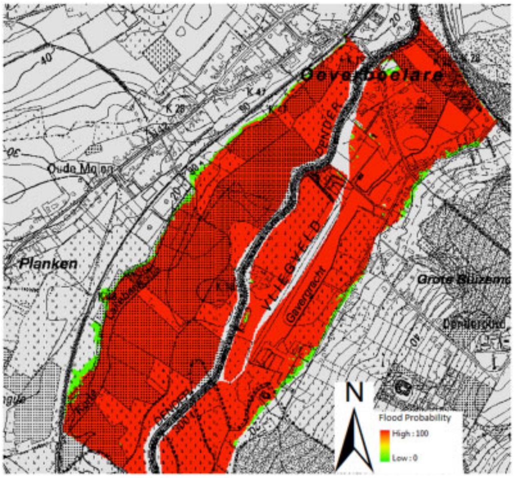

Figure 7. Inundation probability (%) map for the next 48 h for the river Dender at Overboelare on 14 November 2010 01:00.

Figure 8. Observed flood extent derived from helicopter images on the 15*th* November 2010.

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