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Surrogate Modelling for Uncertainty Analysis of Dike Breach Floods

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ABSTRACT

Dike breaches are sudden and severe events that need to be predicted and managed for public safety. Important flood characteristics such as flood arrival times are required for effective decision making. Current tools, such as hydrodynamic models, offer this information at long simulation times to be used during an emergency situation. Surrogate models leave out complex physical descriptions of the system in favour of simplified hydraulic principles. In this study, we couple a conceptual breach outflow hydrograph model with a fast flood arrival time model. The low computation times of the coupled framework allow for 10.000 simulations to be conducted in around 5 minutes. We investigate the effect of two sources of uncertainty on the breach outflow and on the flood arrival times: the uncertain moment of dike failure due to wave overtopping, and the uncertain river water level forecast with a number of days lead-time. The results illustrate that the models effectively compute the breach outflow and flood arrival times, and that the river water level causes greater uncertainty than the wave overtopping failure mechanism. We further conclude that the method shows the potential of surrogate modelling frameworks for flood emergency decision making thanks to the low data demand and computational cost.

KEYWORDS: Levee breach, conceptual modelling, real-time flood forecasting

1 INTRODUCTION

Dike breach floods are disastrous events that threaten the lives and livelihoods of many people worldwide. Before a breach occurs, it is essential that the public is informed in time about flood consequences and is possibly evacuated. Decision makers require indicators such as water depths, flow velocities and flood arrival times (Leskens et al., 2014). The most common tool to obtain this information is a hydrodynamic model of the area at risk. These models capture the physics of flowing water through solving the shallow water equations, and accurately model the flood event as it might unfold (Teng et al., 2017). However, hydrodynamic models are computationally expensive, especially at the large scales of dike breach flood events. The computation times can be in the order of hours to days, which is not in line with the fast response time required by decision makers during an emergency. During such an event, decision makers can benefit from a fast model that can simulate the flood event with the most up-to-date information, and take into account uncertainties that are present in the system (Leskens et al., 2014). The fastest hydrodynamic model simulations might be able to deliver output of a single model run, but an ensemble of runs for uncertainty estimates is not yet possible.

Alternative modelling techniques for fast flood modelling after dike breaches have focused on two main research directions. First, machine learning techniques have been explored by Bentivoglio et al. (2023) and Besseling et al. (2024), for example. These models are able to accurately capture breach flood dynamics after being trained on large datasets of pre-generated breach flood scenarios. The input of the machine learning model is a breach outflow hydrograph, while the output is water depths in the hinterland through time. Research into flood modelling using machine learning is currently focused on the ability of the models to generalise to unseen locations and events that were not present in the training data, and to lower the amount of data required for a model that is applicable in many scenarios.

The other main research direction for fast flood modelling concerns conceptual modelling, which relies on simplified hydraulic concepts instead of detailed physical processes (Teng et al., 2017). Compared to machine learning models, these techniques require less data to operate as they do not need to be trained on large datasets. In order to develop these models, calibrating and validating hydrodynamic simulations may be necessary, but the data requirements for the models themselves are low. Similar to machine learning models, the computation times of conceptual models are sufficiently low to enable uncertainty analysis during emergency flood situations. Currently, the main focus of research in the field of conceptual modelling is on integrating more dynamics in the simulations. For example, a main criticism of these kinds of models is that their use of level-pool flooding can lead to very inaccurate water depths (Sanders et al., 2024). Additionally, these flood models have been able to predict only maximum inundation extents, and not the flood arrival times due to flood propagation that occurs in the hours after a breach. This makes these models largely unsuitable for use in dike breach modelling in flat delta regions. Therefore, there is a need to develop a conceptual modelling framework for dike breaching studies that is able to deliver dynamic flood information on flood arrival times to decision makers fast.

In this study, we evaluate the use of a conceptual modelling framework for uncertainty analysis during a dike breach. It combines the model that generates a breach outflow hydrograph by Besseling et al. (2025) and a fast arrival time model by Besseling et al. (submitted). These models have a low run time, enabling analysis of the effects of uncertainties on the arrival times of the flood after a breach. The novel method is presented in Section 2, with model descriptions for the outflow hydrograph model and arrival time model. The results of the coupled framework are shown in Section 3, with a discussion and conclusion in Section 4 and Section 5, respectively.

2 METHODOLOGY

2.1 Case study

The study area of the research is near the Dutch-German border, where the river Rhine bifurcates into the Waal river and the Pannerdensch Canal (Figure 1). This canal bifurcates again into the Nederrijn river and IJssel river. Between the Rhine, the canal and the IJssel is an area ringed by dikes that is the case study of the research. A dike breach is modelled in the far south-east of the area, and the flood spreads in north-westerly direction (Figure 1).

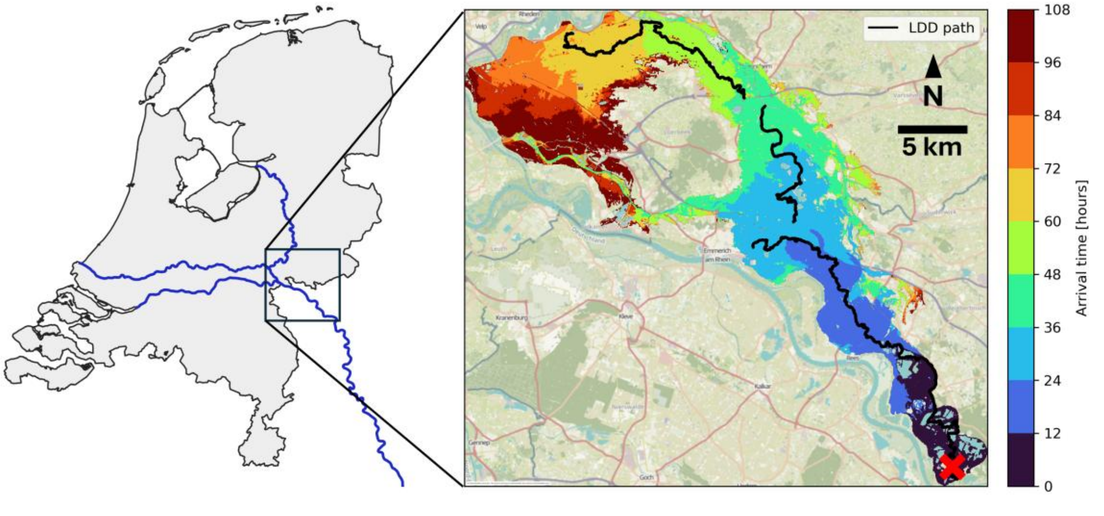

Figure 1: Study area along the Dutch-German Rhine with arrival times of a 10,000 year return period dike breach flood event (breach at red X)

2.2 Breach outflow model

The breach outflow is modelled using the conceptual model proposed by Besseling et al. (2025). A short description of the model is provided here. The model contains three modules: (1) the river water level module, (2) the breach growth and outflow module, and (3) the hinterland water level module.

First, the river water level has to be computed for every time step. The required input is a forecast of the river discharge, which are often available by water authorities through the use of hydrological models and weather forecasts. The forecasted river discharge is converted to a river water level at the dike breach location through the use of stage-discharge relationships that are available for the study area.

Second, the breach growth and breach outflow are computed. For the breach growth, two-stage breach growth equation by Verheij-Van der Knaap (Verheij, 2003) is used. The breach first deepens to the level of the hinterland behind the breach in a pre-defined amount of time. Then, it widens based on the water level difference between the river and the hinterland, with steeper water level gradients resulting in faster growing breaches. The breach outflow is computed using the broad-crested weir equation, first as unsubmerged and later as submerged based on the water level in the hinterland.

Third, the hinterland module uses a 0D approach to simulate the hinterland water level. The water level is computed by dividing the total flood volume up to that time step by the surface area of the hinterland. This eventually leads to the drowning of the breach and the breach outflow being computed by the submerged broad-crested weir equation. However, for larger study areas the water level in the hinterland rises slowly, thereby overestimating the water level gradient and leading to unrealistically large breach growth. Therefore, the model assumes near-critical flow in the breach opening by setting the water level in the hinterland as 2/3 of the river water level. This ratio may be calibrated due to local terrain effects such as elevation differences and friction. The water level using this near-critical flow assumption is maintained until the water level using the volume/area computation exceeds it.

For a more detailed description on the model, we refer to Besseling et al. (2025). The output of the breach outflow model is a breach discharge hydrograph that is used as input for the flood arrival time model.

2.3 Flood arrival time model

The flood arrival times behind the dike breach is modelled using a fast model developed by Besseling et al. (submitted). It is based on the Digital Elevation Model (DEM) of the study area. From the breach location, the steepest downstream path into the hinterland is identified according to the D8-algorithm (Local Drainage Direction, or LDD path). Following an analysis of idealized breach simulations (varying uniform downstream slopes, varying uniform peak breach discharges, varying uniform Manning's roughness), a linear regression model was created relating the flood front's propagation velocity to these idealized parameters.

This linear regression model was applied to the case study scenario (Figure 1). The required input is a peak breach outflow and the DEM of the study area. For each of the grid cells along the steepest downstream LDD path, a propagation velocity and corresponding traversal time is computed. The arrival times of the flood along this steepest downstream path are now known. Besseling et al. (submitted) found that this technique results in accurate arrival time estimates when applied to the case study dike breach of two different return periods: a 100-year return period and a 10,000 year return period. The model predicted near-identical flood arrival times for the critical first 48 hours after the dike breach compared to a process-based hydrodynamic model of the same events (the flood propagates 25–30 kilometres in this time period).

2.4 Uncertainty analysis

Both the breach outflow model and arrival time model are deterministic in nature. Through their fast computation times, the effect of uncertainties on the model output can quickly be analysed. This allows the use of the combined models during a flood emergency.

The dike breach location for the case study is along the German section of the Rhine, so to illustrate the working of the method we extrapolate the Dutch fragility curve for overtopping to a German dike section most upstream in the study area (Figure 1). A breach here significantly affects the Netherlands as well, since the flood propagates downstream parallel to the Rhine river and into the Netherlands. Because of the distance of flood propagation (~50 km for the entire flood event), this breach location can show interesting insight in the effect of uncertainties on the flood arrival times.

In this uncertainty analysis, we analyse the effects of two uncertainties on the breach outflow and subsequent flood arrival times: (1) breach initiation uncertainty due to failure mechanisms and (2) river water level uncertainty due to discharge forecasting lead-times. First, the breach initiation depends on the failure mechanism of the breach, but it is highly uncertain when and how a breach will form. That is why for many dike sections, fragility curves are set up for a number of failure mechanisms. These fragility curves define the probability that a dike will fail at a given water level due to that failure mechanism. We obtained fragility curves for the Dutch dike sections along the Rhine river. Second, the river water level needs to be forecasted, because possible flood risk reduction measures need to be taken ahead of time. For example, evacuating a large area that is possibly affected by the flood requires a considerate amount of time. Therefore, authorities rely on discharge forecasts that have increasing uncertainty for longer lead times. To illustrate the method, we add a fixed uncertainty in the river water level that is normally distributed (mean of 0, standard deviation of 0.1 m). This standard deviation roughly corresponds with the 10-90% confidence interval of a 5-day lead time water level forecast that the Dutch authorities make for the Rhine during normal discharge ranges (see for example Rijkswaterstaat, n.d.). However, this uncertainty could increase even further when forecasting for extreme river discharges.

We conducted three uncertainty analyses. First, we sample 9500 scenarios with different critical water levels from the fragility curve (i.e. the river water level at which the dike breaches) and run the model using a fixed river discharge wave. The discharge wave of interest reflects the design discharge for Dutch dikes along the Rhine under climate change, which has a peak discharge of 18,000 m^3/s. For the second analysis, we sample 9500 river water level uncertainties from the normal distribution described above. The river water level of the design discharge wave is increased or decreased with the sampled amount. These scenarios have a fixed critical water level for all 9500 simulations. The third uncertainty analysis combines both uncertainty sources, generating 9500 scenarios by sampling a critical river water level from the fragility curve and by sampling a water level difference from the water level uncertainty.

Each of the three analyses will result in 9500 breach outflow hydrographs that contain a spread of possible peak breach outflows. The arrival time model then uses these peak breach outflow hydrographs to compute the flood propagation velocity along the steepest downstream path through the hinterland. This results in varying arrival times throughout the flooded area, and an insight in how the fragility curve of overtopping and the river water level forecast affects the flood arrival times.

3 RESULTS

The breach outflow model computes a spread of possible breach outflows for the design river discharge scenario, based on the fragility curve for overtopping and on the river water level uncertainty (Figure 2). The uncertainty in the breaching moment is about 2 days, meaning that the river water level can cause dike breaches from day 13 to about day 15 (peak river water level reached) in this discharge wave scenario. The resulting breach outflow hydrographs vary only slightly in their peak discharge for the wave overtopping uncertainty (Figure 2a). Larger variations are seen for the river water level uncertainty (Figure 2b), and the largest spread in breach outflows is visible for the combined runs (Figure 2c). Earlier breaches have a higher peak breach discharge, because the breach has time to widen before the peak river water level occurs. The total flood volume entering the hinterland also increases for earlier breaches, as there is more time for flood water to enter the hinterland (Figure 2b-d-f).

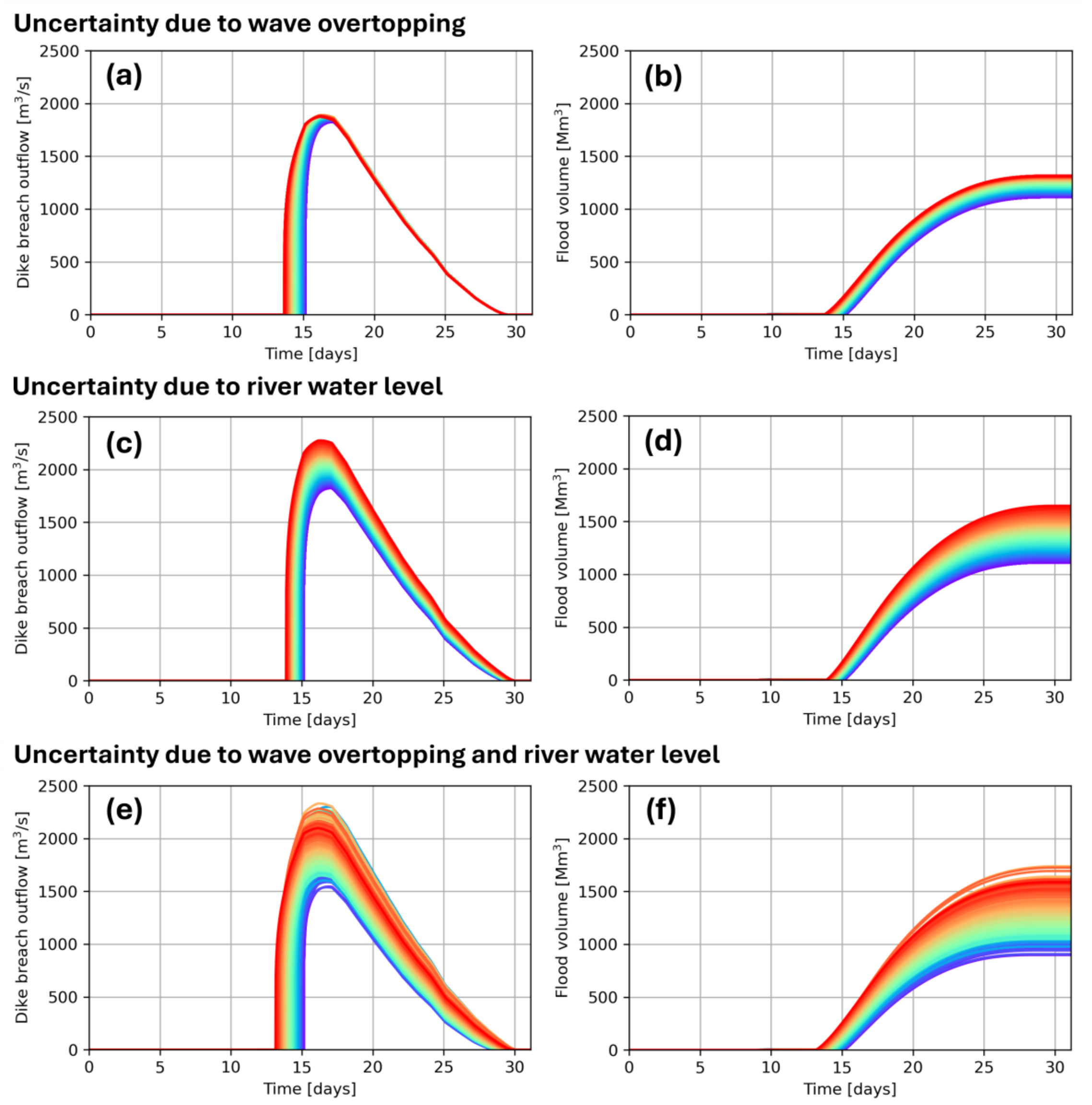

Figure 2: Uncertainty in breach discharge and cumulative flood volume due to **(a-b)** wave overtopping fragility curve, **(c-d)** river water level forecast, **(e-f)** combined wave overtopping fragility curve and river water level forecast. Colors reflect the breach time, with a gradient between early breaches in red towards late breaches in purple.

The resulting spread in peak breach outflow forms the input for the arrival time model. The combined models run the 9500 scenarios in around 5 minutes. The arrival time model output shows the boundary for flood arrival time zones using a thin line (Figure 3). Each line is color-coded to reflect the location of the flood front after a particular time period. Because of the difference in peak breach outflows, different flood propagation velocities are computed for the 9500 simulations. Therefore, the thin lines marking the flood arrival time zones slightly differ per simulation, and a band-width is obtained (Figure 3). This band-width shows the uncertainty in arrival time zone boundaries, indicating how strongly the arrival time is affected by the fragility curve for overtopping and by the river water level uncertainty.

The figure shows that nearest to the breach, the bandwidth for the arrival time zone up to 6 hours after the breach is quite narrow. This means that in the short distance from the breach to here, the difference in propagation velocity caused by the different breaching moments and river water levels is not very significant. Further away from the breach location, the band-widths of arrival time zone uncertainty gradually increase. For the wave overtopping uncertainty, even at the furthest location from the breach, it seems that the uncertainty only amounts to a difference of about 4 kilometers between the slowest and the fastest propagating floods (Figure 3a). However, the spread in arrival times due to the river water level uncertainty is much larger, as the locations of the expected arrival time zone boundaries become quite spread out and even overlap (Figure 3b).

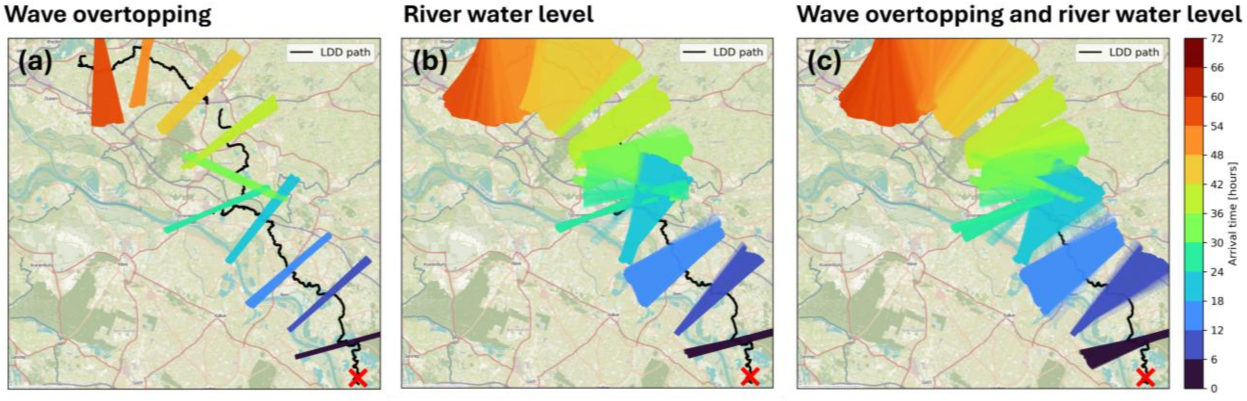

Figure 3: Uncertainty in the location of the flood front for various time periods after the dike breach. **(a)** Uncertainty due to wave overtopping fragility curve. **(b)** Uncertainty due to river water level forecast. **(c)** Uncertainty due to wave overtopping fragility curve and river water level forecast.

4 DISCUSSION

In this study, we present a combination of two conceptual models that model the breach outflow and subsequent flood arrival times for a large-scale dike breach flood. The framework is applied to study the effect of uncertainties like the wave overtopping failure mechanism and the water level forecasts. As a result of the low computational demand, such analyses are now possible during an emergency situation. Decision makers can model the situation as it is unfolding, and obtain a first indication of the flood consequences.

This work illustrates the methodology of the framework, and can be extended to more accurately reflect local conditions and relevant uncertainties. For example, the fragility curve for wave overtopping at the breach location along the German Rhine was derived from available data along the Dutch Rhine. More accurate analysis can include additional fragility curves for dike failure mechanisms of piping and slope instability, if they are available and relevant. Furthermore, the uncertainty in the river water level was included here based on a 5-day lead-time during normal discharge regimes, which was fixed for the entire flood event. However, uncertainty in river water level forecasts generally increases for longer lead-times, so the method can be improved by introducing a lead-time-dependent water level uncertainty. Lastly, we are visually comparing here the effects of the introduced uncertainties (e.g. Figure 2), but the method also allows for a more advanced approach using Sobol' indices (Saltelli et al., 2010), for example. This could illustrate the most important sources of uncertainty in the dike breaching system, and provide directions on which streams of information are most important to focus on clarifying during an emergency situation.

A challenge of the method lies in the coupling of the two models. The arrival time model relies on the assumption that the peak breach outflow forces its way through the hinterland and is the main driver of the flood propagation. The regression model for front propagation velocity was therefore derived using the peak breach outflow that occurs quickly after the breach develops. However, Besseling et al. (2025) showed that the breach outflow hydrograph model can make accurate predictions of the flood volumes and breach outflows, but that the peak breach outflows are underestimated and occur later than in hydrodynamic model simulations of the same event. This limitation causes the arrival time zones to be shifted compared to the actual peak breach outflow values, but the general effect of the uncertainties on the arrival times remains the same.

Future work can extend the arrival time model by including the volumes from the breach outflow hydrographs. The arrival time model defines the extent of the flood along the Local Drainage Direction (LDD) path, but does not yet compute the water depths. Imposing the volume that has entered the hinterland per time step onto the section of the LDD that has flooded, water depths can be computed using the Height Above Nearest Drainage principle (HAND; Nobre et al. 2011). This would make the model applicable in different cases, ranging from flat and open areas to areas which contain flood defences or local terrain that slows down or blocks the flood from propagating until a water level is reached to overtop this structure or terrain feature. The fast method would then allow insights into the flood extent and water depths in addition to the predicted arrival time zones. Authorities can benefit from this additional data for the decision making during an emergency flood situation.

5 CONCLUSION

We propose a framework of coupled conceptual models for flooding after dike breaches, that simulates the breach outflow hydrograph and subsequent flood arrival times. As a result of the low computation times, the coupled models can be used to simulate thousands of flood scenarios in a few minutes. Using the framework, this study presents an analysis of the effects of two uncertainties on the breach outflow and flood arrival times: the uncertainty in dike failure due to wave overtopping, and the uncertainty in river water levels due to lead-times of forecasting. The framework successfully illustrates the effect of these uncertainties, showing that water level uncertainty has a large impact on breach outflow and subsequent flood arrival time. The framework can be used to identify important sources of uncertainty and allow decision makers to make more informed decisions regarding data requirements and evacuation strategies, among other things.

6 ACKNOWLEDGEMENTS

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