Hydraulic modelling approaches to decrease uncertainty in flood frequency relations

Anouk Bomers and Suzanne Hulscher[1]

[1] University of Twente, Faculty of Engineering Technology, Water Engineering & Management

River floods are a major global hazard causing extensive damage and loss of lives. To protect the hinterland from severe inundations, flood defences are commonly designed according to appropriate safety levels that are determined based on a statistical return period. To estimate discharges associated with different return periods, flood frequency analyses are used that fit a distribution to the data set of annual maximum discharges.

The data sets of measured annual maximum discharges are generally in the order of 100 years. Consequently, the predicted design discharges with a return period of e.g. 100,000 years are based on extrapolation and therefore highly uncertain (Figure 1). To decrease the uncertainty of flood frequency relations, historical flood information can be added to the data set of measured discharges.

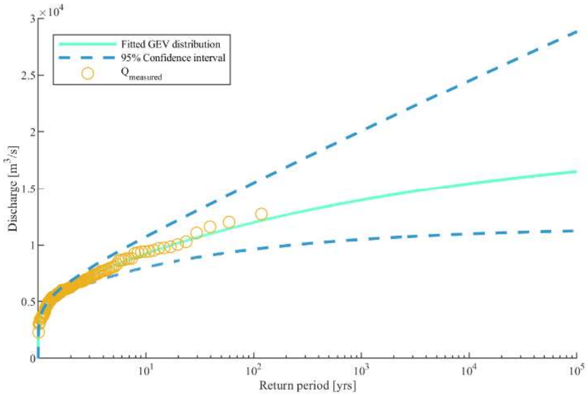

Figure 1: Fitted GEV flood frequency curve based on ~120 years of annual maximum discharge observations of the Rhine river at Lobith (German-Dutch border) and corresponding 95% confidence interval.

During this research (which was part of a PhD project by the first author), we aimed to study the effect of extending the data set of measured discharges on the reduction of the 95% uncertainty interval of flood frequency relations. The data set was extended with reconstructed historic flood events using hydraulic modelling approaches. The Rhine delta was used as a case study (Figure 2), but the proposed methodologies can also be applied to other river basins and coastal areas provided that sufficient historical data are available.

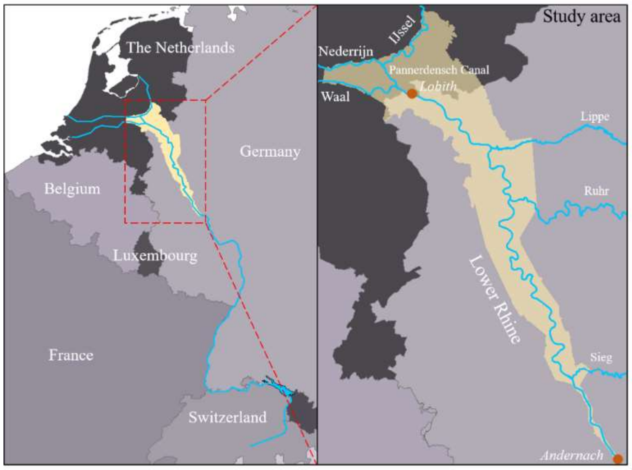

Figure 2: The Rhine river catchment area (left) and the study area (right).

A drawback of reconstructing historic flood events with the use of hydraulic models is the high computational cost. Because historical information is limited and uncertain, many model runs have to be performed to include these uncertainties in the analysis. Therefore, the hydraulic model must be efficient in terms of model accuracy and computational time. We first developed a fully two dimensional (2D) hydraulic model, after which we simplified this model to achieve a data-driven model, referred to as a response surface surrogate model. By simplifying the model, computational times are reduced. However, it is important that the simplified models are still capable of reproducing the desired output.

Various 2D grids were evaluated in terms of model performance. Structured rectangular, unstructured triangular and hybrid (consisting of both structured and unstructured grid cells) grids with a high and low resolution were compared (Figure 3) as well as the performance of both non-calibrated and calibrated models based on simulated water levels. Furthermore, flow velocities in a meander bend were evaluated to assess the correctness of the physical processes. It was found that there are three important grid generated features that influence model results, namely: (1) bathymetry accuracy and (2) numerical friction, both as a result of grid resolution, and (3) numerical viscosity as a result of grid shape. Numerical friction and numerical viscosity have the same effect on model results as physical bed friction has, namely attenuating the discharge wave and in increasing the simulated water levels.

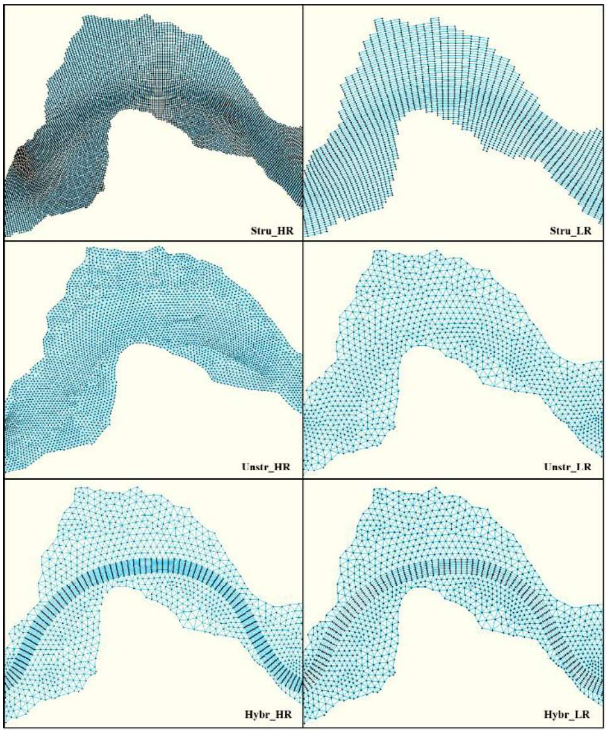

Figure 3: The six grids evaluated in which "Stru" refers to the triangular structured grids, "Unstr" to the curvilinear unstructured grids and "Hybr" to the grids having curvilinear grid cells in the main channel and triangular grid cells in the floodplains. HR and LR refers to high resolution and low resolution, respectively.

A 1D-2D coupled model was developed, also referred to as a lower-fidelity physically based surrogate model, to study whether this model can replace a fully 2D model to reduce computational time. In this simplified model, the main channel and floodplains are schematized by 1D profiles and the embanked areas are discretized on a 2D grid. This model was used to perform a sensitivity analysis to analyse which parameter has the largest impact on the maximum discharges during a flood event. In 1926 the largest measured flood event has occurred. This flood event was used as a case study. It was concluded that the model output is most sensitive to the roughness class with the largest share in surface area. Furthermore, it was found that the 1D-2D coupled model is capable of producing model results with the same accuracy as a fully 2D model. Therefore, the 1D-2D coupled model was used as a high-fidelity model.

A surface response surrogate model was developed with training data created with the 1D-2D coupled model. This data-driven surrogate model has no physical interpretation, but reproduces the input-output relations of the high-fidelity model based on simple mathematical functions. As a result, many model runs can be performed within a couple of seconds. The maximum discharge at Lobith (German-Dutch border) during the 1809 flood event was reconstructed based on measured water levels of surrounding locations. The confidence intervals of the 1809 maximum discharge are reduced compared to the results of existing methods that did not use hydraulic models to perform the reconstruction.

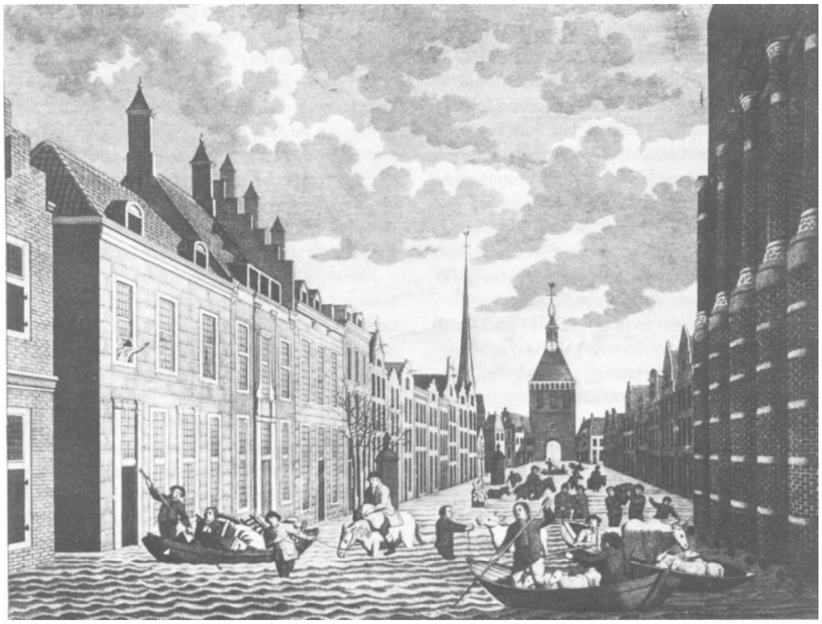

Figure 4: Painting of the 1809 flood event at Culemborg by J. G. Visser.

Before historic flood events can be added to the data set of annual maximum discharges, they must be normalized for natural and anthropogenic changes in the river system. To do so, the upstream discharges of the historic flood events were routed over the present geometry using the 1D-2D coupled modelling approach. The present system behaviour of the Rhine delta as a result of various upstream discharges has been shown. Dike breaches are included in the model domain as random input parameter resulting in various overland flow patterns. As a result, dike breaches and corresponding overland flow patterns may significantly change the discharge partitioning of and flood risk along the Dutch Rhine river branches (Figure 5).

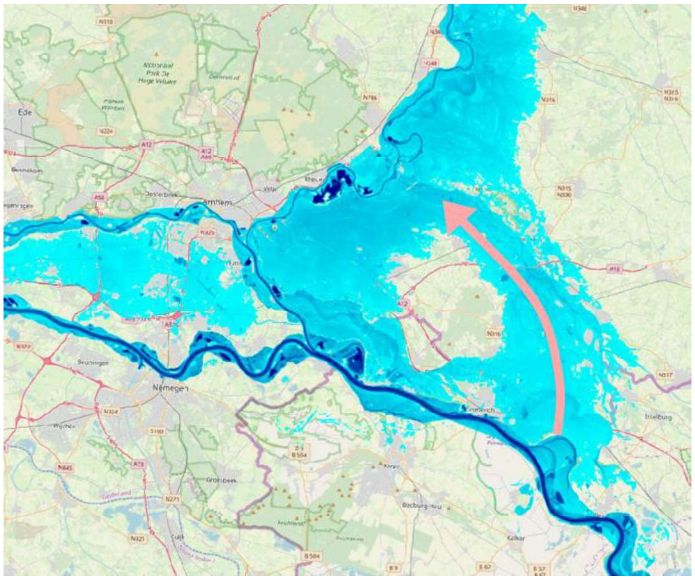

Figure 5: Dike breaches in Germany may result in significant overland flow (pink arrow) resulting in inundations of the Dutch hinterland influencing Dutch flood risk.

Finally, a continuous data set of annual maximum discharges of approximately 700 years was created. The data from the period 1772-2018, comprising of discharge and water level measurements, were extended with 12 historic flood events. The 12 historic flood events were normalized using the modelling approach developed in Chapter 5. Next, a bootstrap approach was used to sample discharges for the missing years in the historical time period, resulting in a continuous series. A flood frequency analysis was performed with the extended data set. The results of this analysis were compared with the flood frequency relation created by solely using measured discharges. It was found that uncertainty in flood frequency relations decreases if the length of the considered data set of annual maximum discharges is extended (Figure 6). Therefore, it is recommended to include as many historic flood events as possible in the considered data set such that the uncertainty intervals of flood frequency relations are reduced. This even applies if the magnitude of the historic flood event itself is highly uncertain. In this manner, future design discharges can be predicted with less uncertainty.

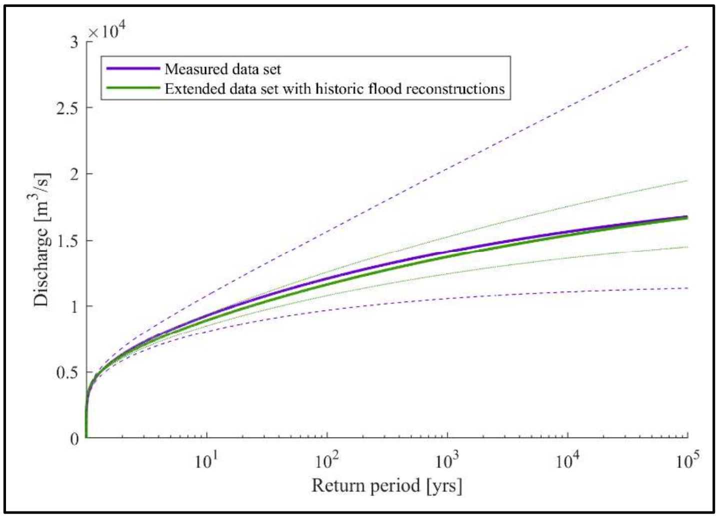

Figure 6: Flood frequency analysis performed with the measured data set of annual maximum discharges of ~120 years and with the data set extended with historic flood events resulting in a data set having a length of ~700 years.

The PhD research by Anouk Bomers was part of the research programme Floods of the Past-Design for the future with project number 14506 (Water 2015), which was (partly) financed by the Netherlands Organisation for Scientific Research (NWO). Anouk Bomers was the recipient of the KIVI Hoogendoorn Fluid Mechanics Award for the best PhD thesis defended in the academic year 2019-2020. For more details on the work, see Refs [1] – [6].

References

1. Bomers, A. Hydraulic modelling approaches to decrease uncertainty in flood frequency relations, PhD Thesis, University of Twente, 2000. https://research.utwente.nl/en/publications/hydraulic-modelling-approaches-to-decrease-uncertainty-in-flood-f
2. Bomers, A., Van der Meulen. B., Schielen, R.M.J., Hulscher, S.J.M.H. (2019). Historic flood reconstruction with the use of an artificial neural network. *Water Resources Research* **55** (11), 9673-9688. DOI: 10.1029/2019WR025656
3. Bomers, A., Schielen, R.M.J., Hulscher, S.J.M.H. (2019). Decreasing uncertainty in flood frequency analyses by including historic flood events in an efficient bootstrap approach. *Natural Hazards and Earth System Sciences* **19**, 1895-1908. DOI: 10.5194/nhess-19-1895-2019
4. Bomers, A., Schielen, R.M.J., Hulscher, S.J.M.H. (2019). Consequences of dike breaches and overflow in a bifurcating river system. *Natural Hazards* **97**, 309-334. DOI: 10.1016/j.envsoft.2019.03.019
5. Bomers, A., Schielen, R.M.J., Hulscher, S.J.M.H. (2019). Application of a lower-fidelity surrogate hydraulic model for historic flood reconstruction. *Environmental Modelling and Software* **117**, 223-236. DOI: 10.1007/s11069-019-03643-y
6. Bomers, A., Schielen, R.M.J., Hulscher, S.J.M.H. (2019). The influence of grid shape and grid size on hydraulic river modelling performance. *Environmental Fluid Mechanics* **19**, 1273-1294. DOI: 10.1007/s10652-019-09670-4