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The discharge magnitude of the 1374 millennium flood event in the Rhine river

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Keywords — historic flood event, hydraulic modelling approach, flood reconstruction, flood frequency analysis

Introduction
Reconstructions of the most severe historic flood events contribute to a better quantification of design discharges corresponding to large return periods. However, reconstructions of the peak discharges of these historic flood events generally have large uncertainties related to the historic topography and hydraulic roughness of the river channels and floodplains (Herget and Meurs, 2010; Lang et al., 2003).
Discharge magnitudes of historic flood events can be reconstructed by using the simple one-dimensional (1D) approach (e.g. 1D cross-sectional) (Herget and Meurs, 2010) or hydraulic modelling approach (van der Meulen et al., 2021). However, the simple 1D approach makes it difficult to account for uncertainties in historic topography and hydraulic roughness. Therefore, this study sets up a 1D-2D coupled hydraulic model to reconstruct the discharge magnitude of the 1374 flood event - considered the largest flood of the last millennium in the Rhine river - in which the river is modelled by 1D profiles and the floodplains are discretized on a 2D grid. The result will be used to evaluate the effect on the design discharge.

Methodology
An "inverse modelling" approach was used to reconstruct the discharge magnitude of the 1374 flood event. First, the 1D-2D coupled hydraulic model was set up with the historic topography of the main river and floodplains corresponding to the year 1374 extracted from a high-resolution palaeo-DEM for the Lower Rhine catchment for 800 AD (van der Meulen et al., 2020) (Fig 1) and the hydraulic roughness coefficient for land cover classes corresponding to the palaeo situation (van der Meulen et al., 2021). An uncertainty analysis was then performed with different river bed levels and hydraulic roughness values (Table 1) to estimate the influence of these uncertainties on the reconstructed peak discharge of the 1374 flood event. The upstream discharge wave was also varied, corresponding to a wide range of peak discharges (12,000-24,000 m^3/s). Next, the simulated water levels were compared with the flood mark (observed water level) corresponding to the 1374 flood event at Cologne to determine the appropriate discharge magnitude.

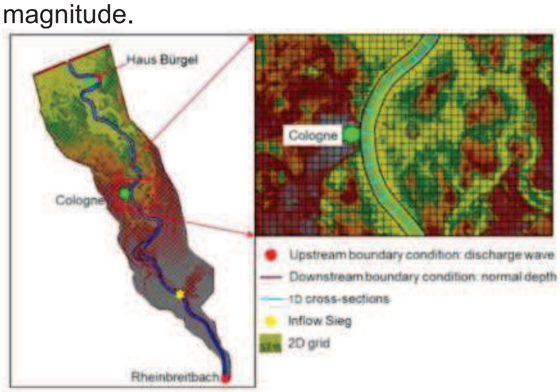

Figure 1. The model set-up for the study area (left side) and a close-up of the 2D grid (right side).

Table 1. Landscape classes and assigned Manning's n values. Source: van der Meulen et al. (2021)

Class	n_{min}	$n_{average}$	n_{max}
High grounds	0.1	0.1	0.1
River bed and banks	0.025	0.03	0.045
Proximal floodplain	0.06	0.07	0.08
Distal floodplain, high	0.04	0.05	0.06
Distal floodplain, low	0.035	0.04	0.055

Results and Discussion
The upstream discharge magnitude of the 1374 flood event was determined to be between 12,500 m^3/s and 22,000 m^3/s considering the combinations of the maximum and minimum roughness coefficient values with different river bed levels, with the 'best' estimate between 14,600 m^3/s and 18,700 m^3/s corresponding to

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the average roughness coefficient value ($n_{average}$) for all landscape classes.

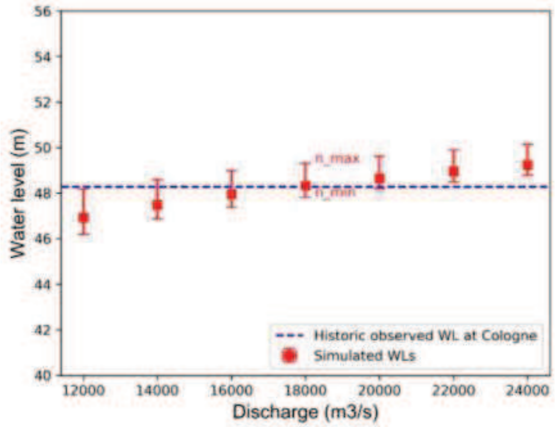

Figure 2. Water level (WL) at Cologne plotted against peak discharge. The uncertainty bands at peak discharge between 12,000 and 24,000 m³/s show results with all roughness classes set to minimum and maximum Manning's n values corresponding to river bed level = 800 AD-3 m. The red marker shows the WLs corresponding to the average Manning's n values.

The reconstructed discharge magnitude of the 1374 flood event corresponds to the study of Herget and Meurs (2010) (23,200 m^3/s, with an uncertainty range of between 18,800 m^3/s and 29,000 m^3/s) and this study were independently updated into the 12 reconstructed historic flood events in the period 1300-1772. Then these data were respectively combined with the systematic discharge data set covering the period 1772-2018 to create a continuous discharge data set covering the period 1317-2018 corresponding to each study by using a bootstrap method (Bomers et al., 2019). A flood frequency analysis was performed based on these discharge data sets to determine the design discharges and their 95% confidence interval for different return periods corresponding to each study based on the generalized extreme value (GEV) distribution function (Fig 3).

The results (Fig 3) show that updating the 1374 reconstructed discharge magnitude of this study into the historic flood events results in a significant reduction of 1,800 m^3/s (10%) in the design discharge and 1000 m^3/s (20%) in the confidence interval corresponding to a 100,000 year return period compared to using the 1374 reconstructed discharge magnitude of Herget and Meurs (2010).

Conclusions

The discharge magnitude for the 1374 millennium flood event was determined to be between 12,500 m^3/s and 22,000 m^3/s, with the 'best' estimate between 14,600 m^3/s and 18,700 m^3/s.

The reduction of the 95% confidence interval shows the importance of reconstructing historic flood events with high accuracy, contributing a more certain quantification of design discharges.

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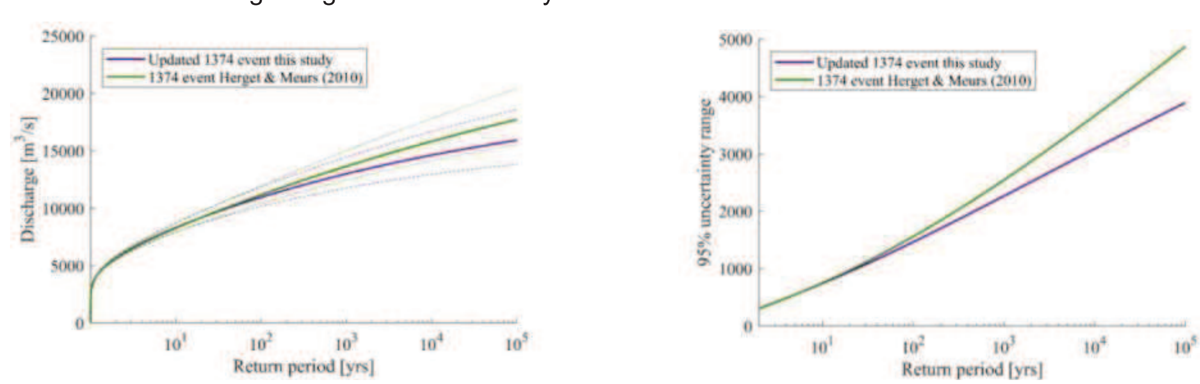

Fig 3. Flood frequency curves and their 95% confidence intervals of data sets corresponding to the reconstructed discharge magnitude of the 1374 flood event of Herget and Meurs´s study and this study.