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# Wall of Waters: Identification of realistic worst-case scenarios for extreme rainstorms and simulation of hazard attributes of resulting flash floods

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## Abstract

Extreme rainfall storms can generate such extreme flash floods that the so-called wall of water phenomenon occurs, which is an immensely fast rise of a wavefront through a street canyon or a natural water course often causing particularly devastating flood damages. This study presents a categorisation method to identify reasonable worst-case rainstorm events from station data that result in catastrophic flash flood events. The identified 24 events were shown to be considerably more extreme than typically employed design storms with a return interval of 100 years. In the selection of the extremes, special care was taken to consider different hazard attributes, which are associated with intrinsically different observed hyetograph shapes, including rectangular, short and long triangle, and double peak shape categories. Hydrodynamic simulations were carried out using the 2D robust shallow water model hms<sup>++</sup> to quantify the flooding impact of the 24 rainfall events in a small urbanised catchment. The simulated hazard attributes showed clear differences as a function of hyetograph shape with strong variations in peak discharges, peak water depths, hazard velocities and flashiness (shortest time to crest). The use of real heavy rainfall series is therefore essential for the generation and further analysis of wall of water events.

## Highlights

- 24 reasonable worst-case rainstorms are identified for safe-to-fail flash flood modelling.
- Design storms considerably underpredict critical wall-of-water hazard attributes.
- Hyetograph shape of extreme rainstorms has a critical influence on hazard attributes.

## Introduction

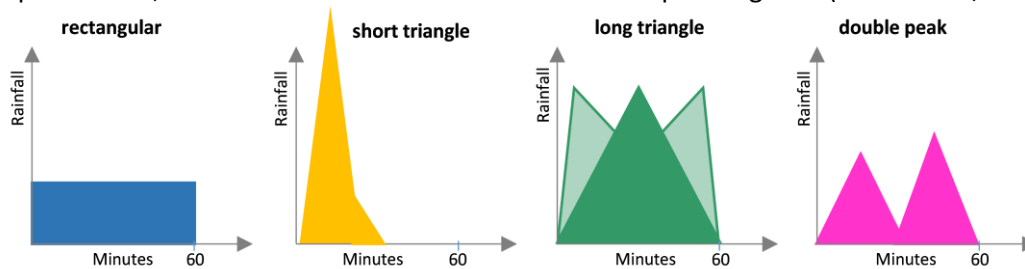
A large portfolio of methods exist to derive design storms to drive flash flood simulations and urban drainage models. Most of these design storms use statistical properties derived from intensity-duration frequency (IDF) curves of long-term rainfall measurements. Many methods, that are based on probability levels or return periods of rainfall intensities, such as the Euler method type 2 (Euler-2), have proven their worth in the past. Studies by Krvavica & Rubinc (2020) found that frequency-based methods such as Euler-2 even tend to overpredict the flow compared to historic events. The assumption that the design storm contains maximum intensities of all durations is thought to be the reason for this overprediction. At the same time, increasingly severe flash floods show that the

triggering rain events were much more violent than we can currently map with a conventional 100-year design rainfall. In particular, rapid heavy rainfall-flash flood events over very short time periods, which lead to the so-called wall of water phenomenon, where a wavefront races through a watercourse that normally only carries very small amount of water *out of nowhere*, are understudied. This study presents the results of a big data analysis of high-resolution precipitation time series to identify reasonable worst-case rainstorms, compares them to conventional Euler-2 design storms and evaluates the resulting hydro-dynamic flash flood simulations with respect to their hazard potential, especially regarding intrinsic wall of water attributes.

## Methodology

### Derivation of reasonable worst-case rainstorms

Almost 200,000 individual files from 954 stations distributed throughout Germany were scanned for particularly extreme 60-min rainfall sums from the 1-min rainfall series of the DWD (German Meteorological Office) for the period 1993-2021. After stringent error evaluation, 896 extreme rain events were chosen and categorised according to their intrinsic hyetograph shape using four typical shape categories (Balbastre-Soldevila et al., 2019): a rectangular, short triangle or long triangle shape (with peak intensities occurring in the beginning, middle or end section) and a double peak shape with two distinct peaks (Figure 1). A final set of 24 reasonable worst-case rainfall series, i.e. potentially catastrophic events, were selected from the four different shape categories (Paton et al., 2024).



**Figure 1.** Hyetographs with four representative shapes, which are used for categorisation: rectangular, short triangle, long triangle (with peak leaning left, centre or right) and double peak shape

### Derivation of Euler-2 design rainstorms

The Euler-2 method is commonly used in European countries for designing urban sewage systems. The Euler-2 design storm used in this study is compiled with station-specific rainfall intensities derived from IDF curves for a return period of 60 minutes and 100 years using the maximal intensities with the same return period but smaller durations including 5, 10, 15, 20, 30 and 45 min (KOSTRA-DWD-2020, 2020). In contrast to simply using a block approach, the Euler type-2 design storm is characterised by a peak with the largest extreme rain intensities within the first third of the 60-minute storm.

### Simulation of hazard parameters of urban flash floods

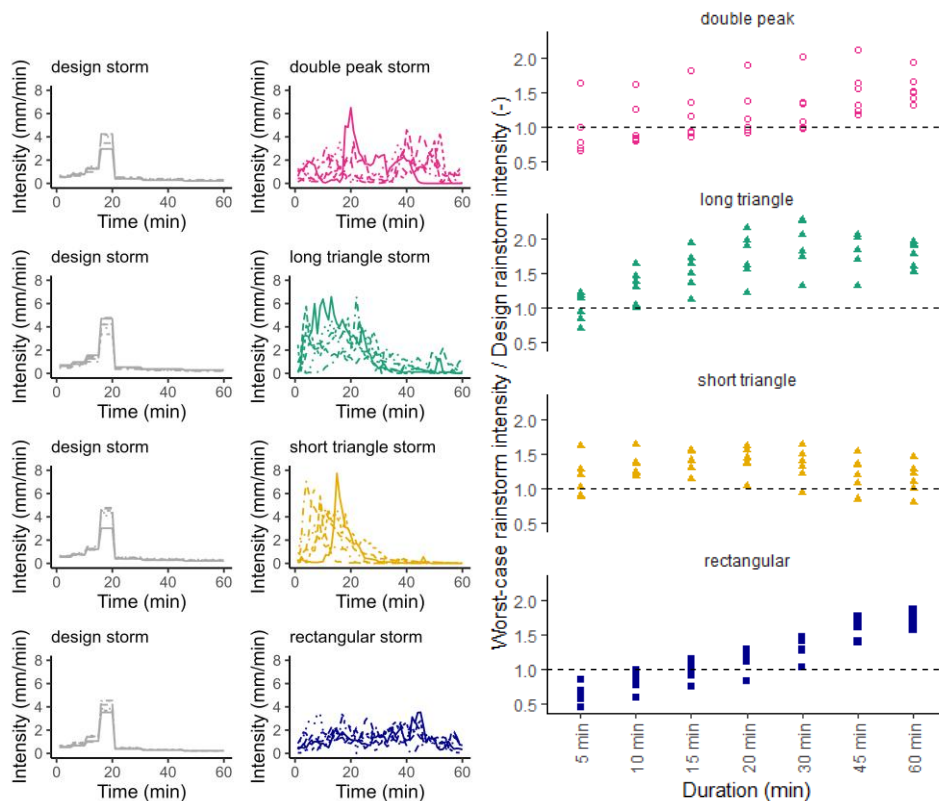
Hydrodynamic simulations were carried out using the 2D robust shallow water model hms<sup>++</sup> (Steffen & Hinkelmann, 2023) to quantify the flooding hazards of the 24 reasonable worst-case rainstorms in comparison to the hazards generated by the commonly used Euler-2 design rainstorm corresponding to the KOSTRA values for the considered catchment. The model domain was set up using a rectangular grid with a spatial resolution of 2 m for the 2.7 km<sup>2</sup> catchment; the drainage system was not included. Simulation results were used to derive hazard attributes time-to-peak, duration of hazard velocity (with mean velocity over 1.75 m/s) and duration of deep flooding (with mean water depths at street level greater than 0.5 m) derived at one flooded high street cross-section at the lower part of the of the catchment.

## Case study

Flash flood simulations were carried out for the semi-urban Wesselbach Valley in Hagen (West-Germany), which is characterised by a steep valley with urban settlements in the lower part and previously forested but recently clear-cut and highly compacted hillslopes in the upper part. The Valley experienced a particularly extreme, unprecedented flash flood in July 2021, leaving a trail of destruction behind.

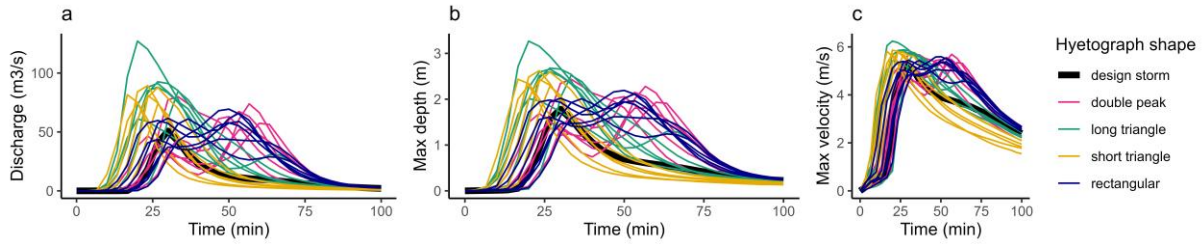
## Results and discussion

A visual comparison (Figure 2, first two columns) between the shapes of the 24 extreme events and the corresponding 100-year Euler-2 design storms shows large divergences except for two short-triangle events. Particularly obvious are the considerably longer high rain intensities of the rectangular events over the entire duration of the event and the much higher (short-triangle) and longer (long-triangle) peaks in comparison to the Euler-2 curves. All selected 24 extreme events except one short-triangle event are considerably larger; the double peak, long-triangle and rectangular ones are larger up to a factor of around 1.5 to 1.8 (Figure 2, third column).



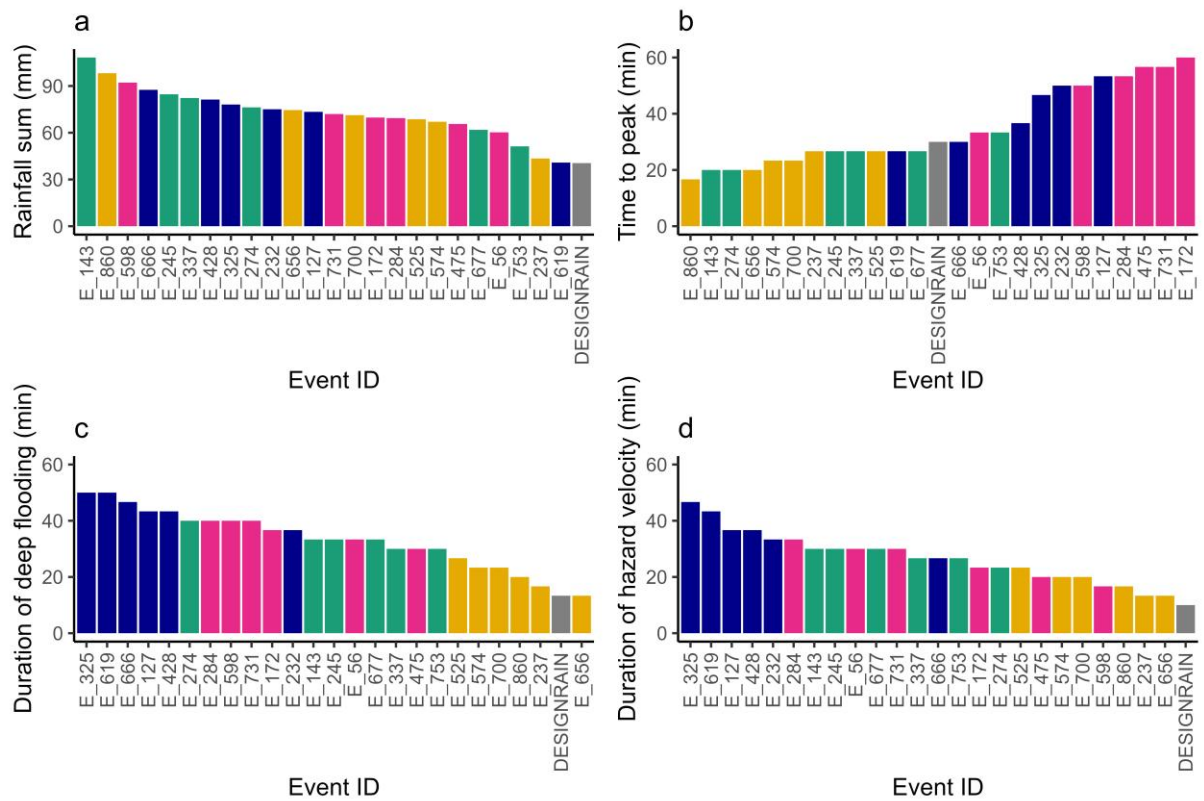
**Figure 2.** Left column: Time series of 24 design storm events (100-year, Euler type-2), middle column: corresponding station data of the 24 selected worst-case rainfall, 6 series for each hyetograph shape, right column: comparison between the 5 min to 60 min intensities of the 24 extreme events with the design storm ones. Dashed horizontal lines mark the events, which have identical intensities; catalogue intensities above and below the dashed line are larger or smaller, respectively than the corresponding IDF intensities.

The hydrodynamic simulations for the Euler-2 design storm quantified considerably lower values for discharge and maximal depth (black line in Figure 3) in comparison to the 24 reasonable worst-case rainstorms (Figure 3).



**Figure 3.** Time series of flash floods generated with the 24 reasonable worst-case rainfall series in 1-min resolution compared to the one of a corresponding 100-year Euler-2 design storm: a) discharge, b) maximal depth and c) maximal velocity along a street transect of the Wesselbach Valley

Clear differences exist in the hazard attributes of the generated flash floods with strong variations in peak discharges, peak water depths and flashiness (shortest time to crest) as a function of hyetograph shape (Figure 4). The short- and long-triangle types generated the fastest time-to-peak. The design storm, derived for the location of the Wesselbach Valley, heavily underestimates duration of deep flooding and duration of hazard velocity in comparison to almost all 24 extreme events.



**Figure 4.** Ranking of flash flood events of the 24 reasonably worst-case scenarios and the 100-year design storm for the Wesselbach Valley with a) rainfall sum, and the hazard attributes of b) time to peak, b) duration of deep flooding with mean water depth within the street section larger than 0.5 and d) duration of hazard velocity with velocity larger than 1.75 m/s. Colour-coding as in previous figures

## Conclusions and future work

The use of real heavy rainfall series with specific consideration of the hyetograph shape is essential for the generation of (modelled) wall of water events, but also for a realistic assessment of different hazard attributes to be considered in future ‘safe-to-fail’ scenarios in order to map the entire possible hazard spectrum of an extreme flash flood. All rainfall series used in this study are freely available (Paton et al., 2024) and can be used for other scenario simulations to derive safe-to-fail scenarios.

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