

## Interactive Discussion: Author Response to Referee #2

# A downward counterfactual analysis of flash floods in Germany

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**RC: Reviewer Comment**,   **AR: Author Response**,    Manuscript text

Dear Referee,

thank you for accepting to review this paper. We are very glad about the positive feedback and about your constructive suggestions.

Please find our responses to your comments below. These should be considered as preliminary (part of the interactive discussion). The final implementation of changes also depends on another referee report.

Thanks again for your efforts!

Kind regards,  
Paul Voit and Maik Heistermann

**RC:** *Abstract: You should define the concept of counterfactual thinking in the abstract, for non-experts.*

**AR:** We inserted a brief explanation after the first sentence of the abstract:

Counterfactuals are scenarios that describe alternative ways of how an event, in this case an extreme rainfall event, could have unfolded.

**RC:** *Line 72 : It would be good to clearly define the time window analysed (e.g. by just adding "between 2001 and 2022" at the end of line 72).*

**AR:** Thank you, indeed, this information is missing there. We added it, as suggested at the end of line 72 of the preprint.

To allow for a detailed representation of the spatio-temporal variability of rainfall, we used the radar climatology product (RADKLIM v2017.002) provided by Germany's national meteorological service (Deutscher Wetterdienst; DWD hereafter) between 2001 and 2022.

**RC:** *Line 113: It might be difficult to do, but I think that a figure illustrating the method and its different stages would make it much easier to understand.*

AR: This point was also mentioned by Referee #1. We will add a plot which hopefully explains the process a bit better to the reader. As this Figure, however, is quite bulky, and as not all readers might be interested in this level of technical detail, we suggest to shorten, in the main article, the explanation of how the catalog was generated. Instead, we provide a more detailed explanation, together with the new figure, in the supplementary material and refer to this in the main text.

Hence, we replaced ll. 113-126 of the preprint by the following shorter text:

The catalog was created by applying multi-step procedure. If we consider the RADKLIM dataset as a 3-D array (one temporal dimension, two spatial dimensions), we first apply a moving 3-D window (72 hours x 3 km x 3 km) to the entire dataset. Within this moving window, the rainfall extremeness is computed for each voxel and for various durations. Afterwards, a clustering algorithm is applied to identify spatio-temporal clusters of extreme rainfall. The details of this approach together with an illustration are provided in the supplementary material.

In the supplementary, we suggest to use the following Figure 1 for illustrating the process (you can find the figure at the end of this PDF because it is quite large):

Referring to this figure, we will explain the process in the supplementary as follows:

The catalog was created as follows (see also Fig. S1) for illustration). For simplification we just used only two durations in Figure S1 (1 and 72 h), while in our actual study we used eight durations (1, 2, 4, 6, 12, 24, 48, 72 h):

1. We applied a 3 km x 3 km x 72 km) moving window for each pixel in the RADKLIM dataset. In Figure S1 a) and b) the pixel is surrounded by a red box. In this moving window we aggregate the rainfall to the durations to respective durations (Figure S1 c) and d). For each duration we calculate the return periods for every pixel in the moving window (Figure S1 e) and f)). Now we can compute the xWEI. The return periods get sorted by decreasing order (Figure S1 g) and h). We then compute the extremeness,  $E_{tA}$  based on Müller et al., 2014:

$$E_{tA} = \frac{\sum_{i=1}^n \ln(p_{t,i})}{n} * \frac{\sqrt{A}}{\sqrt{}} \quad [\ln(\text{year})km] \quad (1)$$

The process is explained in more detail in Voit and Heistermann (2022).

Following this procedure, we get an  $E_{tA}$ -curve for every duration (Fig. S1 i) and j)). The  $E_{tA}$ -curves are placed on a grid (Fig. S1 k)). The  $E_{tA}$ -curves span a surface. The volume underneath that surface is the xWEI-value for the pixel (Fig. S1 l)) which is high, if the rainfall in the 3 x 3 km neighborhood was extreme at multiple durations (between 1 h and 72 h).

2. This way the xWEI-moving window works as a filter for the rainfall data. The result is a dataset of xWEI values with the same dimensions (x, y, time) as the RADKLIM dataset. An xWEI value of ten is approximately equal to an event that had a return period of around 10 years on one duration and at a spatial scale of 9 km<sup>2</sup>.
3. All cells with an xWEI < 10 were discarded (set to NaN) to ensure that there are just cells remaining which signify extreme rainfall. The remaining adjacent cells were clustered based on their neighborhood (pixels within 10 km). This way we obtained distinct clusters where the rainfall must have been exceptionally high.
4. Finally, we determined the bounding box and computed the xWEI value for the entire bounding box, for each identified cluster.

**RC:** *Line 116 : Maybe you could briefly explain how is calculated the xWEI, and give some orders of magnitude.*

**AR:** We refer to the previous answer which now contains more details about the computation of the xWEI.

**RC:** *Line 123: Can you detail "Clustered based on their neighborhood" ? Or show it on an example if you decide to include an illustration.*

**AR:** We cluster pixels with high xWEI values in a neighborhood of 10 km (voxel-based clustering). Also this is now included in the previous explanation.

**RC:** *Line 133: Can you explain why the upper limit is precisely 750 km<sup>2</sup> for the catchment size? Could you give the minimum catchment size?*

**AR:** The basin size for typical flash floods varies among different authors:

- Marchi et al. (2010) and Charpentier-Noyer et al. (2023) define the typical spatial scale "less than

1000 km<sup>2</sup>".

- Gaume et al. (2008) refers to a value of 500 km<sup>2</sup> which has also been used by Matthai (1969) and Stănescu et al. (2004).
- Amponsah et al. (2018) state "catchment scales impacted by flash floods are generally less than 2000–3000 km<sup>2</sup> in size".

Based on these different values we picked a rather small upper limit of 750 km<sup>2</sup> due to our simplistic model.

Regarding the distribution of basin sizes, we will add Figure 2 in the supplementary material.

**RC:** *Table 1: Adding information about impacts (e.g. damage) would help understanding the gravity of these events, which are not well-known by international readers.*

**AR:** Also referee #1 was requesting more information about the events. We included detailed explanation in the supplementary material:

- **LS/Jul02** hit the Harz mountains in the center of Germany with high rainfall sums and lead to flooding of some cities (e.g. Braunschweig). Apparently this HPE did not cause extensive damage as there is not much literature about this event, apart from local newspapers. Furthermore, this event was overshadowed by one of the largest flood catastrophes in Germany just one month later (SN/Aug2002). We can just hypothesize that the event would have caused more damages, had it not happened in the Harz area, which is a watershed. Additionally, there a large reservoirs in this area which regulate streamflow and might have prevented the formation of a larger flood wave.
- **BB/Jun17** caused massive urban flooding in Berlin. This HPE caused the largest insured losses in the period 2002 to 2017 (€60 million) in the greater Berlin area (Caldas-Alvarez et al., 2022).
- The **SN/Aug02** HPE caused extensive flooding in Central Europe (Germany, Austria, Czech Republic and Slovakia). The flooding occurred in the catchments of the Danube and the Elbe. In Germany alone the flood caused 21 casualties and a record breaking damage of €11.6 billion (Thieken et al., 2007; CRED/UCLouvain, 2023).
- Regarding damages, HPE **NW/Jul21** exceeded all previously recorded events even though the rainfall sums were not the most extreme, compared to other historic events (Ludwig et al., 2023). The HPE affected mainly Belgium, the Netherlands and Western Germany. €40 billion damage and 191 casualties (CRED/UCLouvain, 2023) are the consequences of this HPEs.
- The flood following **LS/Jul17** caused damages in the districts surrounding the Harz mountains and the city of Hildesheim (Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz (NLWKN), 2021). According to the DWD the meteorological extremeness of this HPE was similar to the infamous SN/Aug02 event, but due to the location the consequences were not as serious (Becker et al., 2017).
- **BW/May16** was a large HPE across Central Europe which affected Southern Germany. The event included episodes of intense small scale precipitation which caused e.g. the flash flood that partly destroyed the city of Braunsbach (Bronstert et al., 2018). The caused a damage of €2 billion. Euro and 7 deaths (CRED/UCLouvain, 2023).
- Even though **BB/Jun21** displayed the highest daily rainfall sum in Germany in 2021 (198.7 mm, (Becker et al., 2017)) the event did not cause a lot of damage.

- The **BB/Jun20** HPE showed heavy rainfall, especially on shorter durations, in the Brandenburg area and caused smaller floods but did not cause extensive damages.
- Even though the precipitations sums during **HS/May19** exceeded a 100 year return period in many locations, this HPEs did not cause high damages.
- **SN/Jun13** hit central Europe and caused large-scale flooding of many rivers, mainly Danube and Elbe (Schröter et al., 2015). The event caused 4 casualties and an until then unseen damage of €12,9 billion (CRED/UCLouvain, 2023).

And this is the paragraph we will add to the main text after line 231 of the preprint:

Very different levels of impacts were reported for these events. In section S2 of the supplementary material, we put each event in context to other available references (scientific or media), and also attempt to compile estimates of reported damages and loss of lives, if available. While all ten events featured exceptional amounts of rainfall and a corresponding runoff response, only five of them caused massive impacts (SN/Aug02, SN/Jun13, BW/May16, BB/Jun17, and, with by far the highest impact, NW/Jul21) while for the remaining events (LS/Jul02, LS/Jul17, LS/Jul17, HS/May19, and BB/Jun21), the impact was apparently not high enough to attract attention beyond the affected regions. The results of the counterfactual scenario analysis, as presented in the following, should help to understand whether the different levels of impacts for these events were mainly caused by their specific geographic position.

**RC:** *Figure 5: Could the legend be standardised?*

AR: Thank you for this good suggestion. A standardised legend would indeed make subplots a), b) and c) more informative and comparable. We therefore followed your suggestion (Figure 3 in this response letter).

**RC:** *Section 5/ Section 6: In my opinion it would be interesting to discuss the fact that this counterfactual approach is "only" performed from a hydrological point of view (hazard-based). However if you want to go to the bottom of the question "how close actual historical events have already touched upon the worst case scenario", you would need to shift to an impact-based approach.*

AR: We agree that such an impact-based perspective is important. We therefore added the following sentence in line 410

It should be clear that our design of counterfactual scenarios only addresses one single aspect: the spatial position of the precipitation field and its effect on the hydrological hazard intensity. A more comprehensive counterfactual search would require accounting for impact-related aspects and processes. Such aspects could e.g. be the daytime or weekday at which an event occurs, the effectiveness of an early warning chain, or cascading effects of damages to infrastructure.

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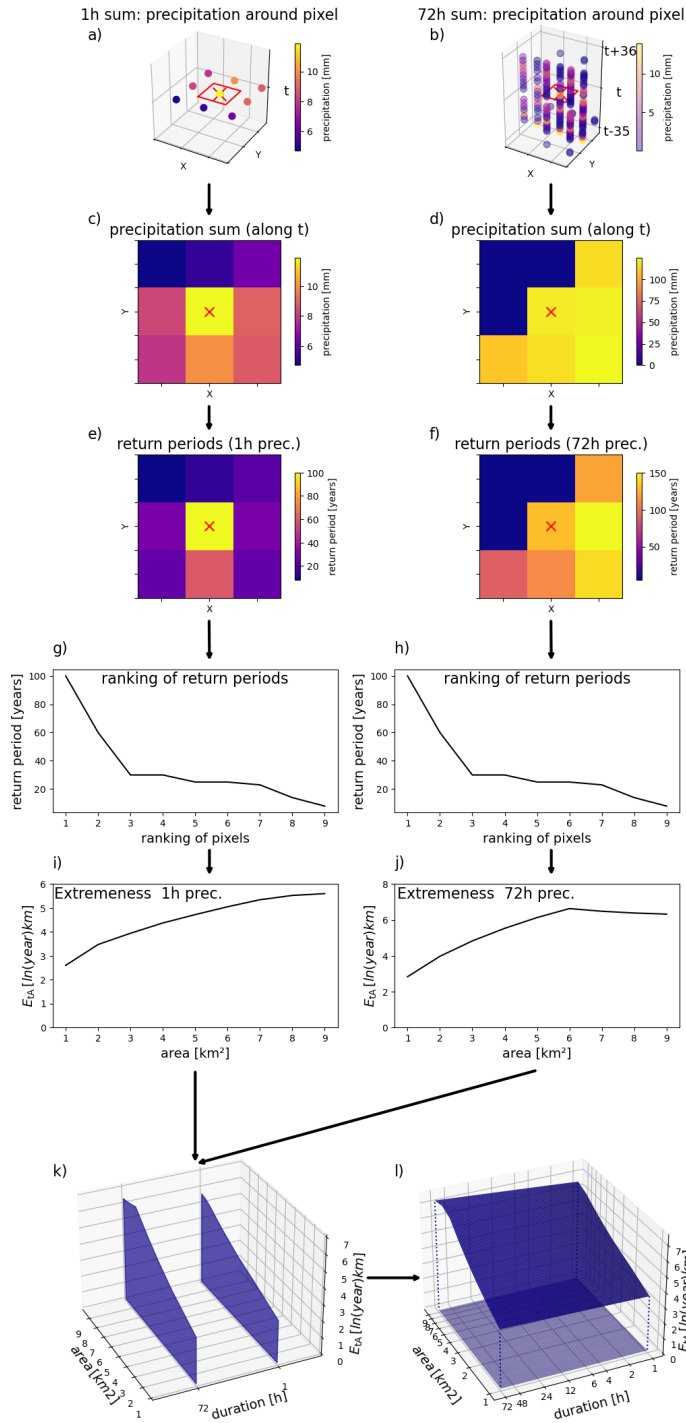


Figure 1: Pixel-wise computation of the xWEI: a) and b) the rainfall data in 3x3 km neighborhood of the for the respective duration. a) 1h precipitation, b) 72h precipitation. c) and d) precipitation sums for the respective durations. e) and f): return periods of the precipitation sums. g) and h): ranked return periods. i) and j):  $E_{tA}$ -curves computed from the ranked return periods. k): The  $E_{tA}$ -curves are placed on a grid. l): a surface is spanned across the curves. The volume under this surface is the xWEI-value of the pixel.



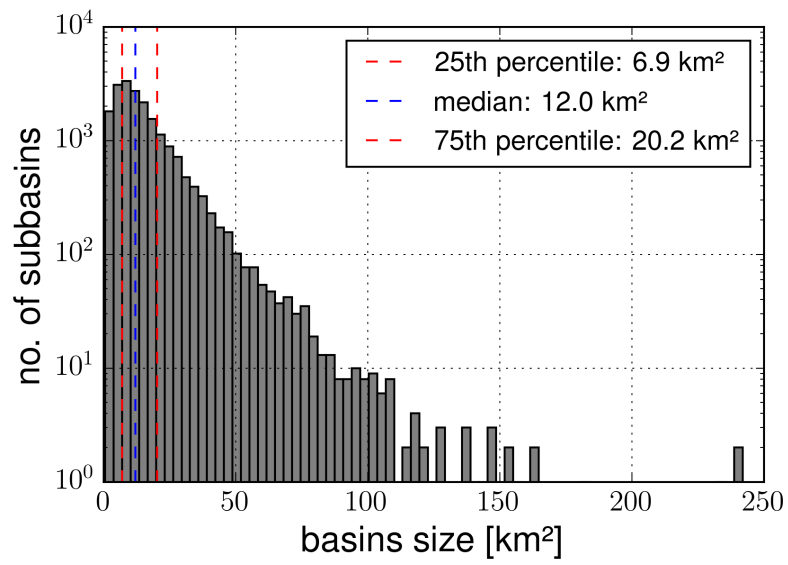


Figure 2: Distribution of subbasin sizes in the study area. The blue line indicates the median size, the red lines the 25- and 75-percentile.

