Overview of major changes

- Extended the motivation of the study in the Introduction by incorporating recent pluvial flood events in Hamburg.
- Clarified the composition of the risk framework in the Introduction, distinguishing between risk to well-being and risk to mobility and accessibility.
- Substantially revised the description of the synthetic dataset in Section 2 (Input Data), incorporating the reviewers' comments and updating Figure 1 and Table 1 accordingly.
- Expanded the hazard characterization and contextualized the modeled event in terms of potential damages (Sections 2.4, 3.1.3, and 4.3.1: Validation and contextualization of model results).
- Improved the readability of Figures 2, 5, 6, and 7.
- Added a new subsection (4.3: Sensitivity, validation, and transferability of the approach) addressing key reviewer comments on transferability and result interpretation.
- Clarified the involvement of multiple stakeholders in the development of the toolbox (revised supplementary material adding Table S1) and expanded the discussion of limitations.

Referee comments # 1

Dear Anonymous Referee,

We cordially thank you for your review and constructive comments which motivates us to further improve the study. We reply to your comments (*italic*) with point-to-point answers (black).

Thanks for your efforts,

Anastasia Vogelbacher, Malte von Szombathely, Marc Lennartz, Benjamin Poschlod, and Jana Sillmann

Major concerns:

- *First, the manuscript would benefit from clarifying what the risk levels calculated here would translate to in a real event. The authors make it transparent that all risk components are context-dependent and their distribution is linked to the spatial scale and the distribution of input variables. However, it is not clear to me what a possible outcome of the risk levels would mean: loss of life, disruptions of livelihoods, material damages?*

We acknowledge that the study would benefit from a clearer explanation of the calculated risk levels and we will provide context both in the introduction (**Line 53-56**) and the results section (**Line 583 ff.**). To this end, we introduce two pluvial flood risk indices: one for well-being and one for mobility and accessibility. The well-being risk index captures potential threats to human health through injuries and worst-case fatalities, and material damages and (time- and cost-intensive) renovations, while the mobility risk index reflects potential limitations in leaving or accessing a building, as well as disruptions to critical infrastructure during emergencies or access to necessary care and medication.

The risk classes (“no risk,” “moderate,” “high,” and “very high”) are used to categorize the relative risk level compared within the study area that a given building will face threatening well-being or mobility, rather than representing absolute numerical values. They are classified using the head/tails break approach, which is tailored to the classification of heavy-tailed distributions. Therefore, the values are always set in relation to all the considered buildings in the study area and will change, if selected buildings change. On the other hand, from the perspective of a practitioner in adaptation planning, this relative classification within the study area of interest can identify (relative) hot spots, which might be overlooked by absolute risk metrics, if the overall level of risk is rather low in the study area.

- *And second, the transferability of the approach should be discussed in more depth. The authors argue that their toolbox could be used in other contexts. They should be more explicit here. Since the toolbox requires detailed and high-resolution input data (which many cities globally do not have the capacity to record and make available), the applicability is limited to context where these data (or similar data) are available. The authors should explicitly state in which kinds of contexts the toolbox is applicable (only in Germany, only in Europe, only in Hamburg, or could this toolbox be used in Nairobi, Tokyo, or Manila?), and who the intended user is. Is the approach more an academic mapping exercise or do the authors think it could be used in disaster relief and adaptation planning, and if so, how?*

We acknowledge that the input data required to use the provided toolbox needs to be at high resolution, which might limit its direct transferability especially due to data availability for meter-resolution pluvial flood simulations. During the development of this toolbox, we worked in close collaboration with city adaptation offices in Hamburg, who were actively involved in its development through three stakeholder workshops and are the main beneficiaries of the toolbox. The toolbox is therefore mainly designed for cities, where similar data is available. In Germany, high-resolution pluvial flood simulations are available across the country (Wimmer & Hovenbitzer, 2025). The toolbox is currently being applied in a Master's thesis on Frankfurt am Main and in a study under review for Hamburg at the building level (cited in the manuscript; von Szombathely et al., 2025). Furthermore, high-resolution urban flood maps are available from the EU project REACHOUT for the cities of Athens, Milano, Logrono, Gdynia (Staccione & Pal, 2024). Additionally, funded by the Copernicus Climate Change Service contract 'Sectoral Information System to support Disaster Risk Reduction', there are high-resolution assessments across 20 European cities(Copernicus Climate Change Service, n.d.). Beyond Europe, there are high-resolution simulations available for New York (Department of Environmental Protection NYC, 2024.) Los Angeles(Sanders et al., 2023), Miami (Sanders et al., 2025), and Houston (Schubert et al., 2022).

Recent advances enabling faster flood simulations (van den Bout et al., 2023) and flood simulations driven by AI (Li et al., 2025) may further increase transferability globally. For the availability of population data and social data, we acknowledge limitations due to data protection and privacy, which vary by country or commune, while high-resolution data might be available at least to the local authorities.

We added a new section (4.3 Sensitivity, validation, and transferability of the approach) and describe this under “Transferability of the method”, Line **590 ff**. for more clarification.

Additionally, by providing the toolbox along with its input data structure and code, we enable its transferability and adaptability to other regions, including those with coarser data resolution (for example, social data), as demonstrated in this work.

We think that scientists and practitioners in the field of climate adaptation planning, urban planning, and water management are potential users of the toolbox, as we co-designed the toolbox together with local practitioners from Hamburg. Based on feedback from the local practitioners, we can state: Now that high-resolution flood simulations are available, water managers and adaptation planners need tools to gain targeted information from these large databases that go beyond a sole overlay of different layers (flood layer, population layer, social data layer). Hence, we believe that the approach can support adaptation planning as it provides a quantified combination of social vulnerability, exposure, and hazard enabling the user to identify risk hot spots.

- *Lastly (and related to the first and second point), the modelling output should be validated in some way. While the sensitivity analysis is an important validation step, some kind of ground-truthing or expert elicitation would greatly benefit the claims of applicability and transferability made in the manuscript. Essentially, the authors should give some kind of qualitative assessment of what the results mean in the context of Hamburg/ their specific study area, and how the results enable decision-oriented risk management.*

This work was developed within the Cluster of Excellence CLICCS, Working Group C1 “Water from Four Sides,” which fosters close collaboration between city stakeholders and local communities affected by multiple severe flood events in Hamburg (Boettcher et al., 2025; Osuide, 2022). In total, the toolbox and its application were discussed extensively during 3 co-creation workshops and presented at 2 workshops with local communities. We will clarify this within the introduction (or methods) section. We will also enhance the methodology description by an overview of represented institutions (**Table S1**) and put them into context to the framework (Lines **136 ff**.).

To contextualize the results, we qualitatively compare the simulated rainfall to two recent heavy rainfall events in Hamburg (2018 and 2024). The May 2018 event in Lohbrügge was classified as an extreme rainfall event (heavy rainfall index classification (Schmitt, 2016) (11/12; >100-year return period) and caused severe flooding, infrastructure damage, major traffic disruptions and evacuations of a few families due to sinkholes (DWD, 2021). The 2024 event in Barmbek reached a rainfall index of 10/12 (>100-year return period. In comparison, the rainfall forcing used in this study (36 mm h^{-1}) corresponds to rainfall index 7 (100-year event), indicating extraordinary but less extreme conditions and therefore potentially lower infrastructure impacts. We added a paragraph within the new section **4.3 "Validation and contextualization of the model results"**.

The underlying assumption for the applied methodology is that once floodwater exceeds a critical threshold (30 cm in the case of risk to mobility and a water level between 30 and 100 cm for well-being), it can hinder cars from passing or entering buildings, respectively. We qualitatively expect that water intrusion leads to structural damage, substantial material losses, and potential risks to human life, including injuries and, in extreme cases, fatalities. Beyond immediate physical impacts, pluvial flooding following intense rainfall events can cause long-term impairment of well-being. Even when individuals survive, severe household disruptions, financial losses, and the need for reconstruction or replacement of property can substantially affect quality of life. These impacts may also include psychological consequences as was shown during the flood in Ahr Valley, such as post-traumatic stress disorder (PTSD) and reduced mental well-being, which are integral components of overall well-being (Augustin et al., 2024; Zenker et al., 2024).

Recommendations for the introduction:

- *I think all three of these points should already be addressed in the introduction. Here, I suggest to also add a paragraph describing the study area in more detail, as well as discuss past or projected pluvial flood events including outcomes (losses and damages).*

We extensively changed the Introduction section following the Reviewer's suggestions (**Line 53-56**, and **85-95**). We further adapted the data description part accordingly, in order to clarify this (Section **2.1**, **Table 1**).

However, the aim of this paper is to present and discuss the developed toolbox and is therefore based on an exemplary case study. We base the synthetic example study area on data from Hamburg to cover a realistic range of variables representing hazard, exposure, and vulnerability, but we distribute synthetic social and population data based on expert knowledge. Hence, our example does not reflect the city of Hamburg (or a specific quarter therein) but a plausible realization of an urban quarter. Therefore, a detailed Hamburg-related description would not make sense in this context.

- *I further suggest to add a paragraph on social vulnerability and where the conceptualizing used in this research is located in the scientific debate (I am specifically missing Susan Cutter's work here, but there are others who have extensively written on household-level vulnerability). A clearer conceptualization of vulnerability would also be beneficial in justifying the choice of input variables for the SV index. I suggest briefly discussing the main intellectual conceptualizations of vulnerability (political economy/ ecology, risk-hazard, ecological resilience) and where the present research positions itself. I highly recommend Susan Cutter's 2024 paper on 'The origin and diffusion of the social vulnerability index (SoVI) as a point of reference.*

Thank you for this detailed comment. The definition and methodological development of the Social Vulnerability Index (SVI) are not the focus of the present study. Instead, we refer to the previously published work (von Szombathely et al., 2023), which is cited in the manuscript. The conceptual foundation, justification of indicator selection, and methodological decisions are described there in detail. That publication also explicitly discusses the conceptual references to, and distinctions from, the work of Susan Cutter. We extended the description of social vulnerability in the manuscript discussing the main intellectual conceptualizations of vulnerability (**Lines 150-175**). We also refer to Susan Cutter’s recent article (**Line 169**).

- *The introduction has relatively generic and could present the argument more clearly. I suggest to not put too much emphasis on increasing global urbanization, but rather Hamburg-specific urbanization and risk trends (past and projected). Again, explicitly making clear in which context(s) the study is set would benefit the manuscript.*

In the presented study, the aim is to develop a generic method for the determination of pluvial flood risk (please see the comment above). Hamburg in this case only serves for the data provision. However, we thank the reviewer for this comment and adapted the introduction and data-description in a clearer way (**Line 53-56**, and **85-95** and Section **2.1**, Table 1).

- *I recommend also adding a few sentences on the hazard type chosen (why pluvial flooding, why not storm surges)?*

We added a few sentences on the chose hazard type in the Indoruction section (L. 53 ff).

While the city of Hamburg is well-known for its exposure to storm surges (e.g. in 1962), recent pluvial flood events gained attention, e.g. after the high-intensity event in Lohbrügge in 2018. We got our inspiration for the urban pluvial flood risk map from the availability of new high-resolution simulations, the increasing relevance in Hamburg (Behörde für Umwelt, Klima, Energie und Agrarwirtschaft und Hamburg Wasser, 2026), Germany (Wimmer & Hovenbitzer, 2025) and globally, exacerbated by ongoing climate change. We are also open to exploring the framework for storm surges - however this is out of the scope of this article.

- *In the methods section or perhaps the discussion, the authors should explicitly state why they are choosing these specific vulnerability indicators and not others (is this a data availability choice or grounded in a clear theoretical framework).*

We extended section *2.2 Social vulnerability: Socio-economic data* to inform the reader about the chosen vulnerability indicator in a clearer way. The social vulnerability index is based on previous work, therefore we kindly refer the reviewer to von Szombathely et al. (2023), where the specific indicators are clearly described and justified. We explicitly state a short summary additionally in section 2.2.

- *The discussion would benefit from a qualitative interpretation of what 'very high pluvial flood risk to well-being' would translate to on the ground. It is unclear to me what kinds of losses and damages very high risk would entail here. An example of a past pluvial flood and its effects could help illustrate the magnitude of risk. In Line 398, the authors note that "On the one hand, the relative risk assessment is a limitation, as the value itself cannot be interpreted (see also Russo et al. 2019)." This presents a significant limitation that warrants further attention. I suggest to revise the manuscript in a way that makes it clear to the reader what the risk calculated here would translate to in a real event.*

We added a paragraph within the discussion section (**4.3.1** & **4.3.2**) to provide “orders of magnitude” of the potential damages based on the conceptualization of the hazard, exposure, and vulnerability as well as qualitative examples from previous pluvial flood events. However, a one to one translation of risk-class to potential damage is not possible, based on the mean-based class distinction, which is dependent on the analyzed buildings (relative risk assessment).

Minor points:

- *The last sentence of the introduction mentions inclusive flood risk planning - was is meant by that? Just based on this statement, the reader would expect the SV index to include specific indicators for marginalized groups (people with disabilities, migrants,* *etc.) - this is not the case, so in what sense is this approach facilitating inclusive risk management?*

We used inclusive as synonym for holistic, but understand the possible misunderstanding. We changed the word accordingly (**Line 100**). Regarding the SV index, we refer to work of von Szombathely et al., (2023) and the previous comments.

- *The indicator "people who have left school without a high school diploma within the past three years" is ambiguous - are these people who left school at some point in the past and have not gained a high school diploma or people who have left school within the past 3 years and not gained a high school diploma? Also, it should be made clear what this corresponds to the in German education system (Abitur? Mittlere Reife?)*

We refer to the last part; “people who have left school within the past 3 years and not gained a high school diploma” and is equivalent to German Abitur or Fachhochschulreife. We clarified this in **Lines 123-125** accordingly.

- *The case study area should be described in a little more detail. Which area of the city was chosen and why? Pluvial flood risk is not equally distributed in the city of Hamburg, so indicators of local risk drivers should be explicitly discussed.*

We understand that the original description of input data was misleading. We therefore rearranged **Table 1** where we not only state the source of the data, but also its application within the case study example.

We would like to clarify that the data is based on hazard simulations and building structure in Hamburg. However, we added synthetic information on population numbers and social data at the building scale, as in Germany, the statistics offices can only provide data aggregated to city quarters. We wanted a synthetic, but plausible small study area as a proof-of-concept for the toolbox application, while we did not want to harm any privacy issues disclosing building locations combined with information on social characteristics. This issue was also closely discussed with city stakeholders. We rephrased section *2.1 Input data* accordingly.

- *It is not clear to me how Bourdieu, 1984 is relevant to constructing indicators of sensitivity and coping capacity. (Line 150: " It is important to ensure that horizontal social distinctions (such as age) contribute to sensitivity, while vertical distinctions (such as income) (Bourdieu, 1984) influence coping capacity.").*

We deleted the corresponding reference.

- *In Line 208, the authors mention first floors are assumed to be used commercially. The wording here is ambiguous, and I assume the authors mean the ground floor?*

We refer to the international first floor which is equivalent to the ground floor in Germany. We added clarification in the text (**Line 127, 193**).

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Referee comments # 2

Dear Anonymous Referee 2,

We cordially thank you for your review, constructive comments and also the positive feedback, which motivates us to further improve the study. We reply to your major comments (*italic*) with point-to-point answers (black).

Thanks for your efforts,

Anastasia Vogelbacher, Malte von Szombathely, Marc Lennartz, Benjamin Poschlod, and Jana Sillmann

- *This manuscript presents a methodological framework for pluvial flood risk assessment at the building scale, implemented through a Python-based ArcGIS toolbox. The concept is relevant and timely, given increasing interest in high-resolution urban flood risk mapping. The paper is clearly written and well structured, and the availability of a toolbox has potential practical value for practitioners. From a hydrology and hazard perspective, however, several important clarifications are needed. Below I list my major and minor comments.*

- *The manuscript repeatedly references von Szombathely et al. (in review) as a source of input data preparation and methodological details. A manuscript under review may not be accessible by readers, and might not be accepted. Critical methodological information should be described directly in this paper. In particular, the description of synthetic input data (paragraph 85) should be expanded.*

We extended the description of synthetic input data significantly (**Line 113 ff**) and modified Table 1.

The cited manuscript under review is published as a preprint and cited in the manuscript, since it contains valuable information. The preprint is accessible here: http://dx.doi.org/10.2139/ssrn.5231006

- *The text states that synthetic building-level data were created and disaggregated from statistical-unit data. Please describe in more detail the disaggregation method and how many realizations are possible and whether the one shown is representative. Building-level risk estimates can convey a false sense of precision, especially when nearly all inputs originate from coarser administrative units*

We thank the reviewer for bringing this to our attention. For our example, we created a realization at the building-level based on expert knowledge, distributing synthetic population numbers and social data to the buildings, which are based on the available, aggregated figures of the statistical area (“neighborhood”). We do not claim that the distribution of population and social data matches the real building-level data from the city quarter, but we are convinced that it represents a plausible distribution, based on the building's sizes and the distribution of vulnerable groups in this statistical reference area of Hamburg. We clarified this in the revised manuscript (section 2.1) and state that we did however not apply a disaggregation routine from the toolbox in this example. The motivation for synthetic building-level data is to show the toolbox capabilities under spatial variability.

However, since we are aware that this high-resolution social data is rarely accessible, we included a simple disaggregation tool within the toolbox which can disaggregate the data from statistical areas to building scale. Thereby, population is distributed linearly according to the living space of each building, while social characteristics are distributed equally across buildings within a statistical area. While statistical areas are supposed to have somewhat homogeneous socio-economic properties, an equal distribution is of course a major limitation underestimating the true risk on a building level (which we do not show in the article). We agree that a more sophisticated disaggregation tool featuring hundreds or thousands of bootstrapped realizations will be a beneficial addition to the toolbox. However, at the current state practitioners from the city authorities might even have access to building resolving data and apply the toolbox on true building level data.

To clarify the data basis in this study, we modified Table 1 (Input data) where we clarify the data source and how it was used in this case study example.

- *The manuscript states the chosen indicators (children <10, elderly singles, no diploma, welfare recipients), but does not justify why these were selected. Were other indicators evaluated? Why were these four selected? If the rationale is only documented in the "in review" paper, then that rationale must be reproduced here.*

The description and evaluation of social vulnerability indicators is described in detail in previous work of von Szombathely et al., (2023) as well as in the pre-print of the cited manuscript (von Szombathely et al., 2025). We extended the description of SV indicators accordingly (**Lines 148 - 173**).

- *Out of curiosity, should building characteristics such as basements used for parking/storage be considered in exposure? Basement flooding is one of the most common and damaging manifestations of pluvial flooding in cities, and it affects both mobility and well-being.*

Yes, indeed this would be a very interesting case to analyze. However, due to data (un)availability we cannot account for this level of detail within the described framework. We describe this limitation in **Lines 476ff**. and in the limitation section, **Line 627**.

As a side note: In the process of the toolbox application in Hamburg, we thought about including the years of construction as a proxy for the existence of a basement (storage), as earlier buildings featured storage under the roof instead of (wet) basements - however, there is not even complete data coverage in years of construction.

- *Paragraph 120 describes the hazard layer as a 36 mm/h event representing a 100-year storm, but essential information is missing. What is the duration of the rainfall? One hour? A design storm? Is the relevant metric rain intensity or resulting water depth? How were water depths obtained: which hydrodynamic/hydrological model was used? What are the limitations of that model? Does the simulation incorporate drainage system performance, clogged inlets, infiltration assumptions, etc.? This paragraph should be split and expanded. The hazard component is currently under-described*

We included a description in Lines 186 -206 in more detail, including the following information to answer the Reviewers questions:

The triggering rainfall event is designed as an hourly 100-year event with an intensity of 36 mm/h according to local rainfall statistics from the German Weather Service (Haberlandt et al., 2023). Thereby, the 36 millimetres of rainfall are distributed along the 60-minute period as Euler-II type design storm (Wartalska et al., 2020) as suggested by the German Association for Water, Wastewater and Waste (DWA) (*Arbeitsblatt DWA-A 118 „Bewertung Der Hydraulischen Leistungsfähigkeit von Entwässerungssystemen" - DWA e. V.*, n.d.).
The pluvial flood simulations are conducted using hydrodynamic model simulations that account for surface runoff, soil infiltration capacity, surface interception, and the capacity of the public sewer network. Clogging effects of inlets and drains are not represented in the simulations. Therefore, the two-dimensional surface runoff model VISDOM (Blöschl et al., 2024; Buttinger-Kreuzhuber et al., 2019, 2022; Buttinger-Kreuzhuber et al., 2022; Waser et al., 2011) is bidirectionally coupled with the Storm Water Management Model (SWMM; U.S. Environmental Protection Agency et al., (2022) which represents the sewer system at one-dimensionally. Model simulations are performed using a digital terrain model with a spatial resolution of 1 m, explicitly incorporating retention basins and drainage ditches.

We would refrain from adding more information on or limitations of the hazard simulation, as the article focuses on the toolbox (that can take any high-resolution water levels as input) and not so much on the hydrodynamic simulations.

- *Paragraph 125 raises an important methodological limitation. It would be very valuable to include (even briefly) a discussion of how results would differ if building-level socio-economic and exposure data were actually available. Could the authors identify a case study with real building-level data to compare against their disaggregation? If not, please discuss the sensitivity of the results to data resolution, since this goes to the heart of the paper's novelty claim.*

We acknowledge that a clear description of input data was needed and adapted this in the revised version of the manuscript as previously described (by enhancing the data description but also the input data Table 1).

The disaggregation is not part of this work, since we used synthetic data on building level (see above). We significantly enlarged the description of the sensitivity analysis and result discussion section 4.3.

At the building level, variance is substantially higher than in disaggregated data, resulting in a wider range of social vulnerability (SV) values. However, since SV represents only one of three components in the overall risk assessment, variability in the final risk estimates is attenuated compared to the SV layer alone. The higher inter-building variability likely leads to less clearly deLineated hotspot structures in this case example, than observed in the application to Hamburg (Preprint of Von Szombathely et al., 2025) . It is important to clarify that our calculations are conducted at the building level rather than with disaggregated data, although the methodological framework allows for such disaggregation, as described in 3.2.2. A direct comparison with real building-level data is not possible due to data protection constraints.

- *Regarding Figure 1. Consider adding an additional panel showing only buildings and roads without flooding to improve readability. Clarify what “building type” means (residential? mixed-use? other categories?).*

We implemented the reviewer’s recommendation and adapted the legend as well as Figure 1. Figure 1h is shown without flood layers to increase readability and highlight the streets layer clearly, representative for all subfigures in Figure 1.

- *The manuscript cites the IPCC risk definition from 2014. However, the 2021 IPCC report provides updated terminology. The paper does not address climate change explicitly, so invoking IPCC terminology may seem unnecessary. Please clarify why the IPCC framework is emphasized, and whether the 2021 definitions are more appropriate.*

The IPCC provides a conceptual framework for conducting risk assessments. As described in the limitations section (Line**s 636 ff**), the risk framework was updated in 2021. The 2021 definition adds the “response” component to the framework. Responses can modify the hazard (e.g. technical/structural adaptation measures), exposure (e.g. resettlements, shifting people from ground floor) or vulnerability (e.g. flood-specific education, funds for affected people, urban planning to mix different social groups). We argue that such responses can partly be assessed using our toolbox with modified input (different water levels, different population data, different social data). Partly, it would require updating components of the toolbox (How does flood-specific education affect the coping capacity of people? How would funds affect the coping capacity?). We discuss this issue in the limitation section and added the differences in the risk framework between IPCC AR5 2014 and IPCC AR6 2021.

- *Hazard section 3.1.3. The paragraph does not clearly connect the earlier mention of the 36 mm/h design storm with the hazard thresholds (30–100 cm).*

The extended description in section 2.4 of the hazard modelling (see above comment) better links the design rainfall to the simulated water level. In section 3.1.3. **Lines 308 ff**. we draw upon it and better connect the hazard definition to the triggering rainfall event. The choice of 30-100cm water level thresholds as thresholds to human well-being is motivated by previous pluvial flood risk studies as mentioned in section 3.1.3 (we refer the reviewer to the cited works of Bhola et al., 2020; Calianno et al., 2013; Lazzarin et al., 2022).

- *Possible typo in Equation 11*

We thank the reviewer for bringing this to our attention. The typo has been corrected (Line **413**).

- *Figure 2: "capacity" is misspelled.*

The typo has been corrected (**Line 219**).

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