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Urban Flood Risk Management: Mapping Potential Impacts of Pluvial Flooding on Elements at Risk

Sarah Lindenlaub[1,2], Guilherme Samprogna Mohor[1,2], Benjamin Creutzfeldt[3], Hanna M. Floto[2], Annegret H. Thieken[1]
Institute of Environmental Science and Geography, University of Potsdam,
Karl-Liebknecht-Str. 24-25, 14476 Potsdam, Germany[1]
E-mail: sarah.lindenlaub@uni-potsdam.de
E-mail: guilherme.samprogna.mohor@uni-potsdam.de
E-mail: annegret.thieken@uni-potsdam.de

UP Transfer GmbH, Am Neuen Palais 10, 14469 Potsdam, Germany[2]
E-mail: hanna.marleen.floto@uni-potsdam.de

Senate Department for Urban Mobility, Transport, Climate Action and the Environment (SenMVKU),
Brückenstrasse 6, 10179 Berlin, Germany[3]
E-mail: benjamin.creutzfeldt@senmvku.berlin.de

ABSTRACT

Urban areas are susceptible to damage caused by pluvial flooding due to sealed surfaces and high property assets in a small area. Pluvial flooding can occur anywhere and is not bound to water bodies, making its impacts hard to predict. Furthermore, the risk posed by such floods is not clearly understood by the general public, which can regularly be observed from citizens careless behaviour, such as driving or walking through flooded areas and underpasses, leading to dangerous situations, injuries and even fatalities. Pluvial flooding cannot only have a negative impact on people, but also cause damage to buildings, disrupt infrastructure services and cause cascading effects. Communicating the potential impacts to raise awareness is therefore an important task, often performed at the municipal level in Germany. One way to translate hydraulic parameters of floods into impact and visual information, is the mapping of its potential results on elements at risk. To operationalize such an impact mapping for the city of Berlin a joined project was established, based on close cooperation of local decision-makers and research. The here presented project results are a further development of the approach by Lindenlaub et al. (2025, https://doi.org/10.5675/HyWa_2025.6_5), focusing on people, buildings, vehicles and points of interest.

KEYWORDS: urban pluvial flooding, hazard maps, impact visualisation, hotspots, risk management, hazard to people, building damage

1 INTRODUCTION

Urban pluvial floods occur frequently after heavy rainfall events and cause huge damages, like in the city of Berlin, where pluvial floods led to damage of €174 million between 2002 and 2021 (Web-1), making Berlin the most frequently and heaviest affected German city (Nikogosian et al., 2021). Although the flow velocity is lower than in mountainous regions, considerable damage is caused, due to Berlin's high density of tangible assets, like buildings, cultural institutions and critical infrastructure.

Currently there is no regulation in place for a standardized development of pluvial risk or impact maps in Germany. An approach applicable throughout the whole country can make an important contribution not only to the technical but also to the political discussion, which is becoming particularly important in the context of the upcoming revision of the German Federal Water Act (WHG). The current draft of the new Flood Protection Act III (HWSG III) no longer only covers fluvial flooding but also defines pluvial flooding as risk and focusses with §79 (Draft WHG) on establishing flood risk maps and detailed analysis of impacts on human health, the environment, cultural heritage, economy and tangible assets (BMUKN, 2024). However, the methodological approach remains unclear. Therefore, research on this topic is of high interest for the municipal pluvial flood risk management.

Here, a methodology towards a more comprehensive impact and risk mapping is presented, addressing several aspects of pluvial flood risks and complementing risk communication. The methodology was developed in close cooperation with local stakeholders and implemented for all of Berlin. The impact analysis was carried out for various elements at risk, namely: people, buildings, vehicles, and points of interest on the micro- (e.g. individual houses) and meso-scale (i.e. indicators aggregated per urban quarter).

Both the micro- and meso-scale provide useful information for various users, such as civil protection, city planning as well as for risk communication towards the general public. Additionally, a cluster analysis on the meso-scale was performed to identify possible hotspot areas. One central aspect during the methodological development was the use of mostly open-source data and of a nationwide standardized pluvial flood scenario (Web-2) to ensure transferability to other German municipalities.

2 METHOD

2.1 Data

The impact analysis is based on an indicative map for pluvial flood hazards published by the German Federal Agency for Cartography and Geodesy (Web-2). This raster map offers modelled maximum water depth and flow velocity for two rainfall scenarios. Our analysis was carried for the extreme event scenario, with a precipitation of 100 mm in 60 min (block rain distribution). The two-dimensional model of the surface runoff incorporates a digital terrain model, cadastral data and the precipitation scenario but does not account for the local sewer network or infiltration into the soil. In addition, terrain details such as culverts beneath roads are not always fully represented. Since the maximum water depth and velocity do not necessarily occur simultaneously, along with the extreme precipitation, it can be assumed that the scenario represents an overestimation and the impact mapping can therefore be considered a “worst case scenario”. The BKG map is the first German-wide approach of mapping pluvial flood hazards that has been agreed upon between all federal states and will be made publicly available.

In addition, official open-source data for buildings, street areas, population density, locations of fire brigades, hospitals, kinder gardens, schools and other points of interest were retrieved from the geoportal of Berlin (Web-3 to -10). Data on cultural sites and non-public data on past flood events were provided by personal communications (SenKultGZ, 2024, BWB, 2025).

2.2 Risk to People

Three factors are important, when analysing the risk to people by pluvial floods: 1) risk to people outdoors (e.g., people stability), 2) risk inside of buildings (i.e., limited vertical evacuation) and 3) the distribution of vulnerable groups (e.g., children and elderlies) (DEFRA, 2006).

1) Flow velocity and water depth are hydraulic parameters that determine people’s stability outside of buildings. The used hazard curves are based on experimental stability tests in water channels summarized by Martinez-Gomariz et al. (2016), describing four hazard classes. The hazard class “low” describes an area where there is generally no hazard and it’s safe also for children. The zone is limited by a water depth (WD) of 0.5 m and a flow velocity (V) of 3 m/s. Additionally the class is limited by the combination of water depth and velocity (WD * V = DV), along the curve of DV = 0.22 m/s^2. The class “moderate” displays an area, where there is a threat to some people, e.g., elderly people with low mobility or kids, which is limited by a) WD = 1.2 m and DV = 0.22 m/s^2, b) WD = 0.5 m, V = 3 m/s and DV = 0.6 m/s^2. In an area with a significant threat is dangerous for most people and the class is limited by WD = 1.2 m, V = 3 m/s and DV= 1.2 m/s^2. Everything above these limits is classified as an extreme threat (for all).

2) Being trapped during a flood in an affected part of a building, such as the basement or the ground floor, and subsequently drowning is a leading cause of death inside of buildings (Thieken et al., 2023).

Being able to evacuate vertically to a non-affected building level can thus reduce this risk. Berlin's flat topography allows a wide horizontal spread of flood water (with exception of local depressions). Therefore, we considered buildings with only one level as "dangerous". This means that houses such as bungalows, which have no vertical evacuation option, are classified as high-risk locations .

3) In case there is a need to evacuate affected buildings it is crucial for civil protection operators to know how many individuals are living in the affected area and how many might need special assistance, e.g. due to mobility issues. There is no clear definition of vulnerable groups based on age limits. In the context of flooding, people over the age of 65 can be considered a vulnerable group, given that this age group is overrepresented among flood fatalities in Germany and several other European countries (FFEM-DB; Papagiannaki et al., 2022, Thieken et al., 2023). Therefore, the age threshold of 65 years is used in the impact analysis. For children, the threshold of (up to) 10 years is used, based on the relationship between body weight and height and data availability in Berlin (DEFRA, Web-5). On the micro-scale (per living block) the total number of residents, children and elderly people can be depicted at once in the following format: XXX|XXX|XXX

2.3 Building Damage

The damage to residential buildings was estimated using the Flood Damage Estimation Tool (FlooDEsT) by Samprogna Mohor et al. (2025). The tool was developed specifically for the estimation of building damage caused by pluvial flooding, given that other damage models, developed for fluvial floods, often lead to an overestimation of the damage for pluvial flood scenarios due to the difference in hydraulic conditions between the two flood types. The recursive partitioning algorithm (XGBoost, Chen & Guestrin, 2016) was trained using household survey data from past pluvial flood events (Thieken et al., 2017; Kellermann et al., 2020).

In its application FlooDEsT uses the hydraulic parameters from the scenario, building polygons and, if possible, building information. In the case of Berlin, the building data is derived from the ALKIS dataset (Web-3). Building damage is only calculated with FlooDEsT for residential buildings and not for objects classified as points of interest (see section 2.5). Missing information and further needed parameters are supplemented by data imputation from the household survey data, which are representative of urban pluvial flooding. As a result, FlooDEsT delivers a relative building damage (percentage of building value) per building. The loss ratios are grouped into four damage classes: low (> 0 bis 3 %), medium (> 3 bis 9 %), high (> 9 bis 16 %), and very high (> 16 %).

2.4 Damage to Vehicles

Driving through flooded area is a commonly observed though dangerous behaviour, which can lead to damage of the engine or electrical system or the loss of a vehicle's stability and can cause injuries and fatalities (Haynes et al., 2009; Thieken et al., 2023). For the impact mapping in Berlin a quite conservative approach was developed together with experts from the local fire brigade.

We distinguished four groups of vehicles, 1) typical civilian vehicles for which the hazard classes 'low', 'medium', 'high' and 'very high' are established; 2) "geländefähig" which are vehicles with a required wading depth of at least 30 cm, commonly used by fire brigades; 3) "geländegängig" which are vehicles with a minimum required wading depth of 60 cm; and 4) special vehicles with an advanced wading depth of up to 1 m. The differentiation of street accessibility based on wading depth between civilian and organizational vehicles is an important information for local civil protection, for example in case of evacuations or emergency calls, while it is possible at the same time to communicate a rather conservative trafficability to the general public.

The four hazard classes for civil vehicles are based on the stability curves summarized and published by Martínez-Gomariz et al. (2017) and are depicted in Figure 1. Aquaplaning is a form of stability loss which is often not included in stability curves and is here represented in the 'low' hazard class. In addition, water can damage the technical system of a vehicle already at reasonably low water depths, therefore the General German Automobile Club (ADAC) suggests a max. trafficable water depth of 20 cm for all vehicles

(Web-11). This aligns with the water depth threshold for the ‘very high’ hazard class (Figure 1). As the trafficability in general is bound to streets, the street area was derived via a buffer from polyline network data (Web-4).

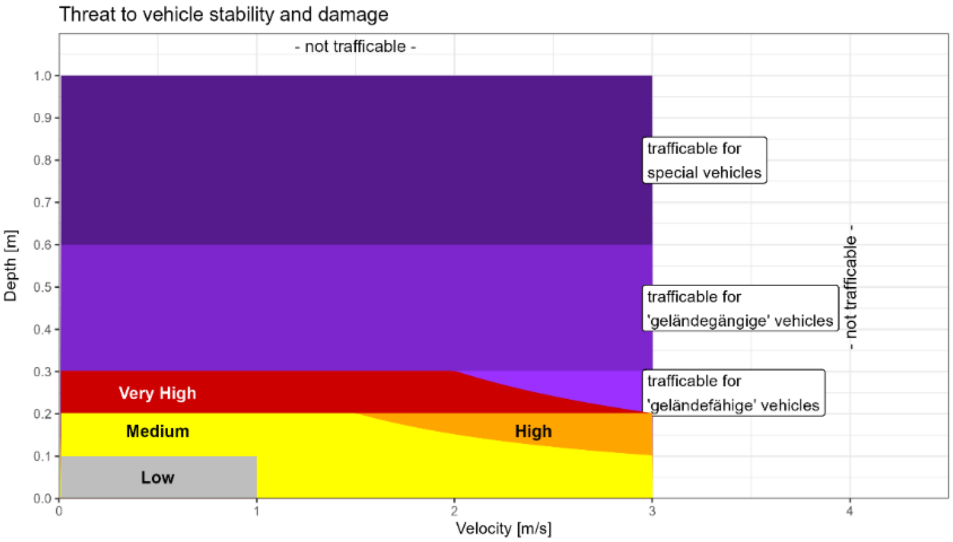

Figure 1: Classification for vehicle stability and damage for civil and organizational vehicles

2.5 Points of Interest

Apart from residential buildings, buildings of public interest or requiring special protection, such as critical infrastructure or cultural and religious buildings, can also be affected by pluvial flooding. Since damage to these “points of interest” (PoI) could either cause cascading effects or require special emergency measures, such as an evacuation of zoo animals or rescuing artworks, the impact on these PoI was determined separately. The assessment was carried out for polygon shapes from the ALKIS buildings data set (Web-3). Here certain buildings were classified as PoI based on their attribute table (“BEZGFK”). The classification was developed in cooperation between local stakeholders as it combines not only critical infrastructure but also other critical objects. Additional locations of PoI were acquired from further official point data (Web-6 to Web-10, SenKultGZ, 2024).

The impact assessment is based on the approach from LUBW (2019) for critical objects, which uses the water depth and flow velocity as criteria and distinguishes four hazard classes (low, moderate, high and very high) as shown in Table 1.

Table 1: Hazard matrix for critical objects, adapted from LUBW (2019)

		Velocity			
		< 0.2 m/s	0.2 to 0.5 m/s	0.5 to 2 m/s	> 2 m/s
Water Depth	< 5 cm	low	low	low	low
	5 to 10 cm	moderate	moderate	high	very high
	10 to 50 cm	high	high	very high	very high
	50 to 100 cm	high	very high	very high	very high
	> 100 cm	very high	very high	very high	very high

2.6 Aggregation on Meso-Scale (Indicators)

An aggregation of indicators on a larger scale, e.g., urban quarters (“LOR-Prognoseräume” by Web-12) offers the opportunity to compare impacts on a meso-scale and allow a hotspot mapping. The following four indicators were calculated per urban quarter based on the results from the micro-scale analyses:

1. Indicator “People Stability”: percentage of area with a classification of ‘moderate’ to ‘extreme’ threat to people’s stability, outdoors (excluding water surfaces and building footprints);
2. Indicator “Building Damage”: percentage of buildings with an estimated damage class of ‘high’ or ‘very high’;
3. Indicator “Vehicle Stability”: percentage of street area classified ‘high’ or more severe threat to civil vehicles;
4. Indicator “Points of Interest”: percentage of PoI with hazard classes ‘high’ or ‘very high’.

2.7 Cluster Analysis

To identify hotspot areas within the city, a cluster analysis was performed, using the four indicators per urban quarter. To overcome their different dimensions, all values were scaled to a range from 0 to 1 per indicator by their minimal and maximal values. In addition to the indicators, deployment data from the fire brigade operations and other reports during past pluvial flood events (BWB, 2025) were considered. The indicator “Report Density” was calculated from the number of reports, divided by the number of inhabitants (Web-5, Web-12) for every urban quarter and afterwards normalized to a scale of 0 to 1.

The cluster analysis was carried out following the procedure proposed by Backhaus et al. (2018). The “Complete Linkage” (farthest neighbor) agglomerative clustering with squared Euclidian distances delivered the best plausible cluster solution. The number of clusters was selected based on the elbow criterion, the increase in the measure of heterogeneity, the dendrogram and Mojena's test (see Backhaus et al., 2018).

3 RESULTS AND DISCUSSION

3.1 Results on Meso-Scale (Aggregation)

The results on the meso-scale (indicators, see section 2.6) show the distribution of potential impacts of pluvial flooding on all elements at risk in the 58 urban quarters in the form of choropleth maps. As an example, the indicator for potential building damage is shown in Figure 2. A maximum of 14% of all buildings are estimated to suffer a ‘high’ or ‘very high’ loss ratio in the urban quarter of “Wilmersdorf Süd”. In ten more quarters at least 5% of the buildings are estimated to show ‘high’ or ‘very high’ loss ratios, while the median value across all 58 areas is 3% for the used scenario.

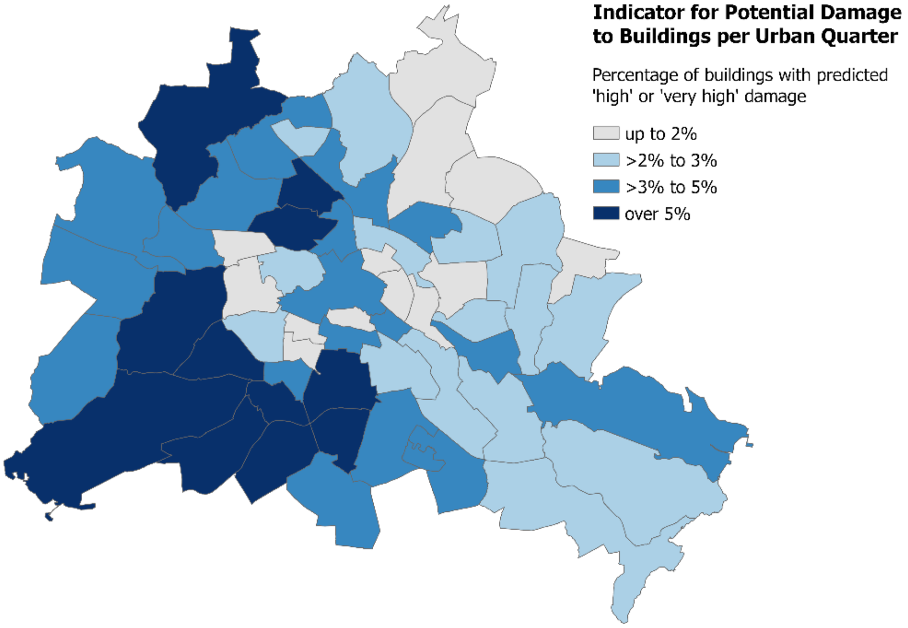

Figure 2: Choropleth map for the indicator “Building Damage” for all 58 urban quarters

3.2 Hotspot Identification

For the „Complete Linkage“ clustering, a five cluster solution was chosen, consisting of three bigger and two smaller clusters. Figure 3 depicts the urban quarters per cluster alongside the mean indicators of each cluster. Cluster 1, with 25 urban quarters, shows below-average values for all variables and is therefore designated as ‘low impact’ (Figure 3). Cluster 2 (20 urban quarter) shows high indicator values for people, vehicles and points of interest. In comparison, cluster 3 shows higher building loss ratios for residential buildings and also high values for PoI and people. Both clusters are therefore labelled ‘medium to high impact’, but show differences in building loss ratios due to the different building structures in the quarters (predominance of one-family versus multi-family homes). The urban quarter “Grüner Norden” was separated into an own cluster, since here the value for the report density is especially high, while the other values are comparatively low.

Cluster 4 shows the hotspots with ‘very high’ potential for pluvial flood impacts for people, vehicles and points of interest, while at the same time also showing medium values for report density. Only the building loss ratio is estimated as low, as the three urban quarters of the cluster “Friedenau”, “Schöneberg Nord“ and “Kreuzberg Süd“ mostly consist of large buildings, where the relative damage is quite low due to the large building sizes.

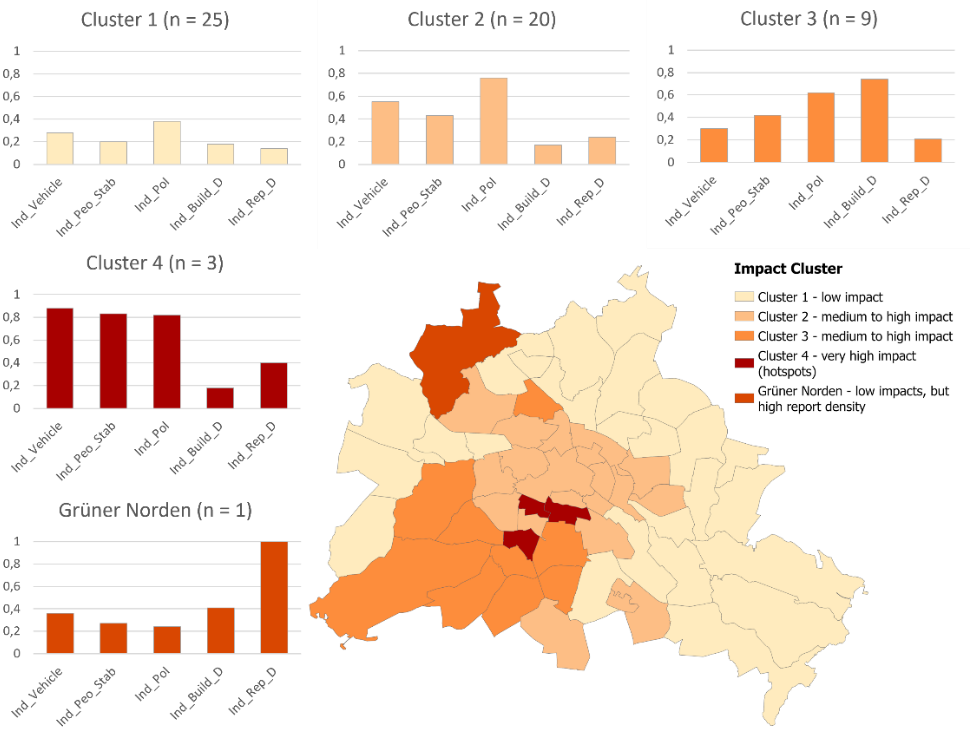

Figure 3: Results of the cluster analysis considering the five indicators: Vehicle Stability (Ind_Vehicle), People Stability (Ind_Peo_Stab), Points of Interest (Ind_PoI), Building Damage (Ind_Build_D), and Report Density (Ind_Rep_D); for all 58 urban quarters

3.3 Results on Micro-Scale

The visualization on the micro-scale can serve for risk communication and for crisis management operations, as it shows possible impacts in more detail. As an example, the combination of the three hazard to people variables are displayed in the hotspot region of “Friedenau“ (see Figure 4). Friedenau is a highly populated urban quarter with a high threat to the people’s stability due to a local depression. An evacuation for this extreme scenario would be very complicated, as there is not only a high risk to people’s stability but also to the vehicle’s stability. In case of an evacuation, the number of residents and of vulnerable people has to be considered, too. At least the vertical evacuation is available in most buildings. Risk communication of urban pluvial flood impacts in this quarter should be one of the central measures, especially because Friedenau has been highly affected by pluvial flooding before (BWB, 2025).

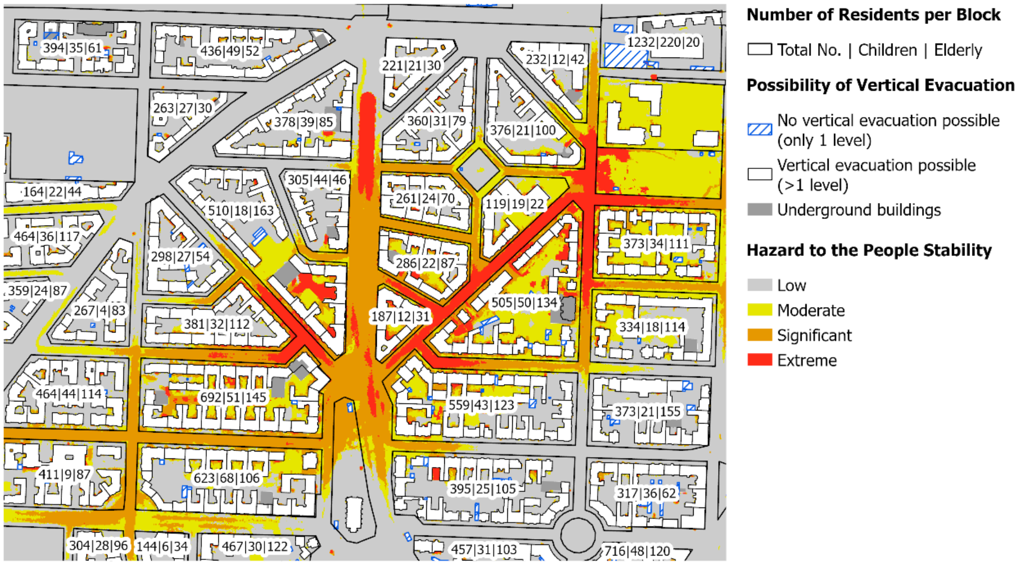

Figure 4: Example of the visualization on the micro-scale, showing the distribution of vulnerable people, the possibility for vertical evacuation and the hazard to the people stability in the hotspot region of Friedenau

3.4 Limitations and Transferability

The impact mapping is bound to up-to-date data, its availability and resolution, which might change when applying the methodology elsewhere. The BKG (Web-2) map on pluvial flooding is the first harmonized, German-wide approach, which is currently the best data basis for a transferable impact mapping, but the map has some limitations. The uncertainties in the results (only max. water levels are provided) and the low level of detail of the hydraulic approach (e.g. no consideration of sewer network) lead to problems in areas such as underpasses and an overestimation of the event's impacts. In regions where more detailed risk maps, with several scenarios, are available, these should be used instead. Still the BKG (Web-2) map can be used for a first impact mapping.

When applying the methodology to other regions some data sources have to be supplemented. Population density data in Berlin is accessible on a very high resolution, which might lead to privacy issues in other regions. Nonetheless, for all of Germany the Census data at 100 x 100 m resolution (Web-13) could be used. The ALKIS building data should also be available in all federal states, but the data availability and quality varies. Building data and information on PoI could be derived from OpenStreetMap data instead.

Due to a lack of data no information can be provided on other vulnerable groups, such as people with long-term illnesses or those in shared accommodations for people needing intensive care, although this would be of great importance for operational crisis management.

There is a high risk in underground parts of buildings, such as basements and underground car parks (Thieken et al. 2023). However, data sets on this topic are incomplete or unavailable and their specific flood impacts therefore cannot be mapped. Nevertheless, information on this risk should be included in any risk and crisis communication as a precautionary measure.

4 CONCLUSION

Pluvial flooding after heavy rainfall is becoming an increasing problem for urban areas. Mapping its impacts can support a better understanding of the potential challenges involved in dealing with such events. As part of the methodological approach, potential impacts on various elements at risk were assessed for an extreme rainfall scenario. Along the micro-scale, a meso-scale assessment was carried out at the level of urban quarters, resulting in the identification of three hotspot areas through a cluster analysis. The quarters “Friedenau”, “Schöneberg Nord“ and “Kreuzberg Süd“ would potentially suffer very high impacts if such an extreme precipitation occurred. Both the micro- and meso-scale results can provide useful information for different users, such as municipal flood risk management (spatial planning and risk communication) and crisis management operators. The approach can easily be transferred to other municipalities, adding value to the current gap of pluvial impact mapping in Germany.

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