A Methodological Approach to Municipal Pluvial Flood Risk Assessment Based on a Small City Case Study

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Abstract: Urban flooding caused by heavy rainfall confronts cities worldwide with new challenges. Urban flash floods lead to considerable dangers and risks. In cities and urban areas, the vulnerability to pluvial flooding is particularly high. In order to be able to respond to heavy rainfall events with adaptation strategies and measures in the course of urban development, the spatial hazards, vulnerabilities and risks must first be determined and evaluated. This article shows a new, universally applicable methodical approach of a municipal pluvial flood risk assessment for small and medium-sized cities. We follow the common approaches to risk and vulnerability analyses and take into account current research approaches to heavy rainfall and urban pluvial flooding. Based on the intersection of the hazard with the vulnerability, the pluvial flood risk is determined. The aim of the present pluvial flood risk assessment was to identify particularly affected areas in the event of heavy rainfall in the small German city of Olfen. The research procedure and the results have been coordinated with the city’s administration within the framework of a real laboratory. In the course of the science–policy cooperation, it was ensured that the results could be applied appropriately in urban developments.

Keywords: heavy rainfall; pluvial flooding; vulnerability assessment; risk assessment; spatial analysis; urban planning

1. Introduction

Climate change is unequivocal and is leading to an increase in the frequency and intensity of extreme events (e.g., storms, floods, heat waves or heavy precipitation events) worldwide. The resulting risks are not only influenced by climate change but also significantly by land use changes. Urbanisation and the associated land uses are leading to increasing risks, especially in urban areas [1–3]. Heavy rainfall events will very likely become more intense and more frequent due to climate change and the increasing global mean surface temperature [1,2]. Already since the 1950s, an increase in the frequency or intensity of extreme precipitation events has been reported worldwide [3]. As a result, serious flash flood events will also occur more frequently in Europe, causing deaths and widespread damages in areas at risk [4]. On average, the annual loss caused by the many flash floods is almost equal to the major river floods that occur once in a century [5]. In the European Union Member States, the total economic losses caused due to weather and climate-related extremes in general over the period 1980–2017 accounted for 83 percent of the monetary losses and were estimated in excess of EUR 426 billion (in 2017 Euro values) [6]. However, there is no statistically significant positive trend in normalised flood losses over the past few decades in Europe, as the increase in observed flood losses is mostly caused by socioeconomic shifts [7,8].
Europe is one of the most urbanised regions worldwide with a share of 74 percent of its population living in urban areas [9]. Cities and urban areas are particularly at risk of pluvial flooding, due to the share of highly sealed areas, urban expansion and the concentration of people and economic assets [10–13]. In addition to climatic changes (increase in the intensity and frequency of extreme events), changes in land use, urbanisation or economic development influence the exposure and vulnerability of the population and assets in endangered areas. These dynamic and interdependent developments have a major impact on the increasing spatial areas at risk [9,13–15]. Not only the influence of ongoing climate change will intensify the negative consequences of heavy rainfall events or flash floods in the future but also social and economic factors such as population growth and land use changes [14,16,17].

Many European countries already suffer from significant consequences due to flash floods that regularly occur after heavy rainfall [18]. The challenges for municipalities in dealing with extreme pluvial flood events are complex and not easy to address, as the examples of previous significant flood disasters in Europe show. Not only large cities or regions but also smaller or medium-sized cities—for instance, the city of Doncaster (UK) in 2007 or, in 2016, the cities of Simbach and Braunsbach (Germany)—need to handle the consequences [1,19]. Rumbach (2016) states that many approaches of disaster researchers are only based on experiences of larger cities [20]. He focused on the characteristics of small Asian cities that are important for disaster risk management and can be transferred to the European context. Small and medium-sized cities experience the same risks that are associated with urbanisation but in contrast to larger cities without the attendant capacity for, e.g., integrated risk assessment. They often have less redundancies regarding financial and human resources, infrastructures or less specialised administrations and a lack of personnel [20]. Birkmann et al. (2016) considered the size of the city in relation to its vulnerability. They show that small and medium-sized cities have stronger barriers in dealing with heavy rainfall than large cities because they are particularly vulnerable and susceptible to natural hazards and climate change and often have limited capacities for resilience building [21]. To address the risk of urban flooding, knowledge and awareness of heavy rain hazards and water-sensitive urban planning are crucial [9].

We conducted an internet and literature search, taking primary and secondary sources into account. The systematic review included a search for specific, topic-related keywords (e.g., heavy rainfall, urban pluvial flooding, exposure, vulnerability, damage potential or spatial analysis) in scientific literature databases as well as guidance documents targeting practitioners.

Current research often uses a comprehensive risk or vulnerability concept, taking into account different components of hazard/impact/ exposure and sensitivity/vulnerability analysis [15,22–24] and/or combined risk [17,25–27]. Nevertheless, the studies differ in their approach and focus. Studies of urban flooding caused by heavy rainfall use data on buildings and infrastructure at different spatial levels [17,28], social and economic factors [17,22,29], damage potentials [18,30–32] or insurance claims based on previous events [33]. Some studies also combine analysis results with pluvial flood risk management or the strengthening of urban resilience [25,34,35]. Other studies have used land use change and urban development models in combination with hydraulic models to simulate and compare adaptation options and their impact on damage potential (cost–benefit analysis) [31].

There is a growing number of studies that use different approaches of vulnerability analyses depending on the individual research objectives. These studies consider various characteristics as determinants of vulnerability which have already been compiled and reflected in existing literature reviews by different authors. The most commonly used characteristics to determine the social component of vulnerability, according to the results of [36], are wealth, age and ethnicity. Arca-Jíménez et al. (2018) state that most of the approaches regarding flash floods predominantly focus on the physical dimension instead of the social dimension of vulnerability. Many studies seem to address the economic dimension of vulnerability mainly through damage estimations [22]. Based on a literature review of recent studies with similar approaches, a number of variables that are commonly used to assess the different components of vulnerability towards pluvial floods were selected and
presented in Table 1. Many studies take into account several indicators to represent the different dimensions of vulnerability (e.g., [15,22,29]).

| Dimension | Variable | Source |
|-----------|----------|--------|
| physical  | number of floors | [22,37] |
|          | construction period/year | [22,36] |
|          | building structure/resistance/condition | [15,22,37] |
| social   | population density | [18,25,29,36–40] |
|          | people with illness/disabled people | [15,25,29,41] |
|          | lone parent households (with dependent children) | [29,36,39] |
|          | ethnicity/ethnic minorities | [29,36,39] |
|          | age | [15,25,29,36,37,39,41] |
|          | (single) pensioner households | [29,39] |
| economic | income | [15,22,29,36,39] |
|          | unemployment | [15,22,29,36,39] |
|          | (level of) education/qualification | [15,29,37,39] |
|          | damages to infrastructures, structures and contents/loss | [15,38,42,43] |
| environmental | land use | [16,17,26,29,30,38,41,42,44] |
|          | land use change | [37,45] |

There is no one-fit-to-all risk index and related set of indicators. Indicators should be selected in accordance with the purpose of an analysis. Consequently, we included variables of different dimensions in our analysis, to emphasize the importance of considering various vulnerability components within the framework of a comprehensive risk assessment for an already built-up area whose population and infrastructure stock are at risk. The analysis serves as an evidence basis for an integrated urban development concept and aims to identify and prioritise particularly affected areas as well as corresponding adaptation strategies and measures. The central objectives of our case study were to identify built-up areas of the city of Olfen with a particularly high pluvial flood risk. The analysis should concretise the resulting need for action and adaptation requirements, also due to other urban planning deficiencies (e.g., functional or structural weakness) within the settlement area. The results and findings serve as a basis for the assessment of the existing flood risk and for the derivation and definition of goals and measures in the municipal urban development concept to alter these risks. The underlying approach of the municipal pluvial flood risk assessment follows in detail.

The city of Olfen is a small, rural town with a population of 12,865 (2019) in the state of North Rhine-Westphalia (county of Coesfeld) and covers an area of 5243 ha (see Figure 1). It is located 45 to 80 m above sea level on the southern edge of the Münsterland region, which can be typically characterised by a low relief energy [46,47]. The city of Olfen consists of two clearly separated districts: the city centre of Olfen and the village of Vinnum (1025 inhabitants), which is around five kilometres southeast [47,48]. In the north, the river Stever flows directly past the city, while the Dortmund-Ems-Canal runs approximately two kilometres further east and the river Lippe approximately five kilometres south. Approximately 17 percent of the city area is settlement and transport area. Regarding the built-up areas, most of the city is characterised by a high share of residential use combined with mixed use in the centre and commercial use particularly in the eastern part. The flat surrounding landscape in which Olfen is embedded predominantly consists of agricultural land, widely fields, forest areas as well as floodplains [49]. Due to its location between the rivers Stever and Lippe, Olfen is regularly affected by fluvial floods. As the retention areas of Stever and Lippe are of sufficient size, the risk potential from these fluvial floods is practically non-existent since the entire built-up area is located outside the floodplains [50]. However, in the recent past, Olfen has been repeatedly affected by heavy rainfall events. Especially in the summer months of 2013 and 2014,
storms with heavy rain and strong winds have caused damage ubiquitously in the entire urban area. These events have revealed information deficits, which are addressed in the following assessment.

Figure 1. Area of investigation: (left) location of the city of Olfen in the state of North Rhine-Westphalia, Germany; (right) urban structure of the city of Olfen.

2. Data and Methodology

2.1. The Risk Assessment Approach

The following approach is based on the risk understanding of the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Office for Disaster Risk Reduction (UNISDR) [3,51], which defines risk as the result of the combination of hazard and vulnerability. The approach (see Figure 2) focuses on these two components which determine the risk: hazard and vulnerability. The component of exposure was not directly taken into account because the approach aimed at the identification of spatial hotspots for flash flood risks at a citywide level. Therefore, exposure was already integrated when analysing the vulnerability. On the contrary, indirect effects may take place outside the directly exposed area due to disruptions of infrastructure services. Criticality was excluded from the vulnerability component, because we used a place-based concept. However, criticality should be considered as an important factor when evaluating the given risk and defined priorities for risk management [52].

Figure 2. Risk assessment approach.
2.1.1. Pluvial Flood Hazard Assessment

In order to assess the pluvial flood hazard of the city of Olfen, an existing heavy rain hazard map was used, including a flow path and sink analysis (topographical analysis, ESRI ArcGIS 10.5) as well as a two-dimensional (2D) surface runoff calculation (hydrodynamic model, ANUGA Software, Geoscience Australia and the Australian National University). For this purpose, a digital terrain model was first created and plausibility checked on the basis of the flow paths and sink analysis. For the runoff accumulation, the laser scan data with a grid size of $1 \times 1$ m from the state of North Rhine-Westphalia were used (Digital Elevation Model 1, DEM), which are provided as open data. The terrain model was then edited and corrected so that, for example, buildings are included in the model as flow obstacles that cannot be flowed through. This digital surface model (raster DSM) was also processed at road crossings, railway underpasses or overpasses or water culverts that are not at the same level. At some road culverts, but also at culverts of water bodies, terrain depressions were identified, where, in reality, runoff is possible. Consequently, the culverts were reworked in the terrain model at coordinated points. In order to include them in the model, they are cut free in the surface model. The local conditions are taken into account and the terrain points are lowered to the height of the riverbed or road surface over the width of the culvert. In the present model, mainly, road underpasses under road embankments and water culverts were reworked. The model ensures that all relevant flow paths can be adjusted and the real conditions are represented in the best possible way.

Based on this model with the adjusted corrections, the final sink calculation and runoff accumulation was carried out. By linking sinks and flow paths, each sink can be assigned to an area that supplies the respective sink with water. With the help of simplified hydrological approaches, it is possible to estimate the volume that accumulates in the sink during a particular model rainfall event. For the flow paths, especially confluences and gradient changes along the flow path give hints for endangered areas during heavy rainfall. The flow path and subsidence data represent a citywide topographic analysis, but due to the lack of a concrete load case and a certain probability of occurrence, they are only conditionally suitable for the analysis of heavy rain hazards and risks.

For the 2D surface runoff calculation, this terrain model is converted into a triangular model (triangulation) and calculated for concrete precipitation events. The effect of the sewer system was not considered in the model, because the model rainfall exceeds the capacity of the sewer system by far. The surface model consisting of triangular elements is directly irrigated. The water runs off following the topography and collects in depressions, sinks or dams. Results are water levels and flow velocities for each triangular element. During the calculation, the complete shallow water equation (dynamic wave approximation) with local acceleration, convective acceleration, friction and gravity is solved for the triangular elements, so that very realistic calculation results can be assumed. In order to also consider inflows into the urban area, the model boundary is oriented to natural catchment areas of water bodies and the topography so that the actual model area is larger than just the evaluated urban area. In addition, the model distinguishes between different surface conditions. For this purpose, the land use data were summarised in 9 categories (e.g., settlement areas, traffic areas, forest or agricultural areas) to which roughness coefficients were assigned. Infiltration was neglected, as the heavy rainfall scenario is based on saturated soil.

The German Weather Service (DWD) provides precipitation data via the so-called KOSTRA Atlas (Coordinated Heavy Precipitation Regionalisation and Evaluation of the German Weather Service). The KOSTRA-DWD-2010 (published 2016) is based on the data for the years 1951–2010 and indicates a precipitation height of 50 millimetres (mm) per hour (h) for the city of Olfen at load case Tn100 (statist occurs every 100 years). The model was thus sprinkled accordingly. This model rainfall was set as block rain in 12 equally strong 5-min intervals. After the 60-min precipitation event, a further 60-min follow-up time is calculated to represent the complete runoff process. In addition, an extreme scenario with a precipitation height of 90 mm/h was chosen. The selected extreme scenario corresponds approximately to the heavy rainfall event in July 2014 in Münster, where 292 L per square metre was measured in only seven hours, one of the highest values in all of Germany since the beginning of
weather records in 1891. Münster is located in the centre of the Münsterland region, which gives it its name, and Olfen belongs to this region. Moreover, it corresponds with the increase factor for extreme events which was proposed by the German Association of Water and Waste Management (DWA) [53]. Therefore, it was obvious to base the present study on a similarly extreme scenario.

The results were processed in a heavy rain hazard map and include the flood extent (area representation), flood depths (water depth in metres, m) and flow velocities (along the flow paths in metres per second, m/s). All determined impoundment depths can be represented on the basis of 2D surface runoff modelling. For a citywide investigation of particularly affected areas, buildings and infrastructures, however, meaningful threshold values must be set. In order to obtain an assessment of areas with special hazards, hotspot areas in the city of Olfen are identified. This is done at the level of building blocks, as the risk of heavy rainfall is to be countered with urban development and resilience measures. The hazards are therefore recorded on the basis of different water spreading volumes in predefined building blocks. The water spreading volume is calculated by multiplying the values of water spreading depth with the water spreading area (water spreading volume in cubic metres, m³). As the building blocks have different area sizes, the size of the building block is also included in the determination of the hazard, so that a comparable statement can be made about the hazard of the individual building blocks (average water spreading volume in cubic metres per square metre building block).

2.1.2. Vulnerability Assessment

Within the following approach, two dimensions of vulnerability are considered: physical vulnerability and social vulnerability. When providing guidelines for planning, it is always important to focus on more than one dimension of vulnerability. Urban pluvial flooding can lead to material (e.g., damage to property, buildings), immaterial (personal injury, environmental damage, damage to cultural assets) and indirect damage (failure/impairment of systemic function) [54,55]. The hazard analysis identified areas that are potentially affected in the event of a heavy precipitation event. In addition to the hazard, however, the vulnerability must also be considered, which refers to damage potentials of the objects located within the endangered areas as well as the inhabitants (and their sensitivity) located in these areas. The determination of the component of vulnerability focuses on two aspects: damage potential, as a representative for physical vulnerability, and the population sensitivity, as a representative for social vulnerability.

Damage Potential

The following risk analysis refers to an object-related flood risk in order to determine the damage potential. This is a common indicator for assessing vulnerability towards disaster risk as shown in our introduction. However, the greatest challenge to adequately determine the damage potential is the existing data situation. There are different ways to quantify the potential damage that a building could sustain from a pluvial flood event. Due to the fact that we had set ourselves the restriction for the analysis that we wanted to use data available in small and medium-sized cities, no direct quantification of damage potentials was carried out. Instead of quantifying the damage potential with a total or expected loss value based on unit damage costs [30] or loss assessment reports [15], we focused on an iterative approach with close cooperation with the municipal administration. Since no usable datasets were available to generate the potential extent of damage, the extent of damage was approximated by means of type-specific expected values. It was necessary to build the analysis on existing municipal datasets, so the building use was the main data basis for determining the damage potential. In order to assign the damage potential to each building use, damage potential levels were conducted based on [54].

The assignment of the types of use to the classes was based on four damage criteria. The first criterion is the building fabric, because every building, whether it is a shed, residential building or a school, can suffer damage to the building fabric during a heavy rainfall event. For this reason,
all building usages are assigned to at least damage level 1. Apart from the building fabric, all other criteria can substitute each other. The second criterion is based on the building services of all occurring building uses. As building services, we define building components, which are necessary to maintain the main function of the building use. The third criterion involves the presence of high-quality furniture that increases the damage potential. For this purpose, building uses were classified by the city administration with regard to the probability of the presence of high-quality furniture. For each building use, assumptions were made on the basis of representatives regarding the value of the interior. The fourth and highest level refers to existing basements, which have a considerable influence on the damage potential. For this purpose, the city of Olfen has made an allocation on the basis of the building age classes and under consideration of the approval procedures. In general, it can be stated that the majority of the buildings in Olfen built after the year 2000 do not have a basement anymore. This procedure was qualified by several site visits.

The delimitation of the levels depends on the applicability of the individual criteria. For example, the highest damage potential level, four, can only be reached if all the criteria for building use described above are met, while the first level applies to all building uses (see Table 2).

| Damage Potential Levels | What Has Been Damaged? |
|-------------------------|-------------------------|
| 1. low damage potential | building fabric - - - |
| 2. medium damage potential | building fabric building services - - |
| 3. high damage potential | building fabric building services high asset furniture - |
| 4. very high damage potential | Building fabric building services high asset furniture basement level |

Once the damage potential levels have been assigned at building level, the values are aggregated at the level of the previously defined building blocks. To avoid distortion due to different building block sizes (larger building blocks have a higher total value), the values are calculated down to the number of buildings, so that average values are generated for the building blocks. The result allows statements to be made about which building blocks have a low, medium, high or very high damage potential.

Population Sensitivity

In addition to the building use and characteristics, the residents located within the building must also be considered when assessing vulnerability. In order to determine the social level of vulnerability, official resident registration data of the city of Olfen were used. The complexity of the social vulnerability component, the various research approaches and the possible indicators is multidimensional. As comparable studies have shown, the selection of suitable indicators depends not least on the available datasets. In our case study, only a simplified vulnerability could be assessed, since the population data only allow statements on absolute numbers and age. In cooperation with the city of Olfen, the general state of health, the presence/absence of the ability to swim as well as the dependence on help from third parties could be converted into sensitivity levels according to peer groups.

The population data with detailed addresses were cleaned up and classified to peer groups based on the age of the household members. To construct these peer groups, different characteristics of the sensitivity of individual age groups to heavy rainfall were determined on the background of the literature review and also discussed with the relevant actors in the city of Olfen. Population sensitivity levels are proposed below, which relate, in particular, to assumptions about health status, swimmer or non-swimmer status and reliance on third party help. The first population sensitivity level consists of peer groups which are more likely to be physically able to save themselves (general health status and swimmers) in the damaging event and would therefore not be dependent on third party help. The population sensitivity level 2 comprises the peer groups of 10–18 and 61–70-year-olds.
This distinction is based on the assumption that these peers are rather more sensitive compared to the group in population sensitivity level 1. The third population sensitivity level contains the peer groups aged 3–9 and 71–80 years. It is to be assumed here that persons in these groups are dependent on the help of third parties in the event of an incident. The highest population sensitivity level comprises the peer groups aged 0–2 and over 80. These two groups belong to the highest sensitivity class based on the assumption that they are generally unable to save themselves, presumably cannot swim, and especially the group of people over 80 have a worse health condition (see Table 3). With this approach, we go beyond the general status quo as described in Section 2, by focusing not only on the particularly young or particularly old population groups but also on the entire population composition.

Table 3. Population sensitivity levels.

| Population Sensitivity Levels | Peer Groups          |
|-------------------------------|----------------------|
| 1. low population sensitivity | 19–25; 26–40; 41–60 |
| 2. medium population sensitivity | 10–18; 61–70       |
| 3. high population sensitivity | 3–9; 71–80          |
| 4. very high population sensitivity | 0–2; ≥80            |

In order to aggregate the levels to the building blocks, a multi-stage procedure was necessary. First, a sensitivity value was calculated for each registration address. This is based on the number of persons per registration address multiplied by the corresponding value of the sensitivity level. This sensitivity score was then averaged on the basis of the buildings before it was summarised on the layer of building blocks. This approach allowed us to take into account not only the qualitative characteristics of the age groups but also the quantitative distribution of the population over the municipal area. Thus, the frequent occurrence of artificial hotspots of old or young populations could be avoided by linking them to all age groups and also by considering the number of inhabitants. The sensitivity values at the level of the building blocks, as well as the damage potential, were then subjected to a normalization process in order to combine these two components into vulnerability. In the case of the chosen approach, the minimum/maximum normalization was used for the indicator calculation, in which each actual value \( x \) of a building block \( g \) at time \( t \) is set in relation to the value range \( (\max_t - \min_t) \) [56]:

\[
Z^t_g = \frac{x^t_g - \min_t}{\max_t - \min_t}
\]

The result is therefore a value per building block between 0 and 1. If a building block has a very high actual value \( x \) (e.g., the hazard), this value will be close to 1 in the normalised form. After normalizing both components, they had been additively linked to a vulnerability. Both components were additively linked to each other, because the city of Olfen as addressee of the assessment placed equal weight on both components.

2.1.3. Pluvial Flood Risk Assessment and Process of Validation

The final pluvial flood risk assessment consists of the combination of all analysis components. In a final step, the determined hazard and vulnerability were combined to obtain the pluvial flood risk. Therefore, both components were additively linked together and again normalised via a min–max normalisation. The linking was carried out additively, as there is no building block in the city area that is neither at hazard nor vulnerable. As a result, the objectively determined risk could also be visualised on a pluvial flood risk map for the city of Olfen. The overlapping of flood hazard with the vulnerability components results in the pluvial flood risk. Only the combination of the information in the spatial risk allows an assessment of the situation on site, since a hazard situation without the presence of the vulnerability or a high vulnerability without hazard does not represent a risk [54]. For the identification of hotspots, which are used for further consideration and derivation of options...
for action and measures, it is imperative to use maps of flood hazard and vulnerability in parallel, since information can be lost when damage potential and hazard are intersected [57].

It should be noted that the risk determined still must be subjected to an evaluation by the city of Olfen. Therefore, a discussion process about measurement data and evaluation standards took place, which led to a consensual result. On this basis, and taking into account the worthiness of protection or the criticality of buildings and infrastructures, specific and effective protection and adaptation strategies and measures were then developed. The definition of adaptation requirements or protection needs depends on the priorities chosen and the political focus. For example, concrete protection goals can be formulated for critical infrastructures such as water and energy supply or social infrastructures such as kindergartens, schools or medical centres. Aspects of systemic relevance and criticality as further basis for evaluation include the significance of individual infrastructures that a failure would have on the functionality and maintenance of the city as a whole. The results should only be converted into a strategy for action once the risk assessment has been carried out as a political–normative process, in which a clear distinction between value and subject level must be considered. The acceptance and transparency of the results is of particular importance for further pluvial flood risk management.

In the course of the analysis work, the existing real-world laboratory of the RESI-extrem project was used. This included individual data and basis as well as existing local knowledge, involving all major stakeholders of the city of Olfen. Consequently, the modelling and simulation work was consistently supervised and the relevant municipal actors were informed about the progress and the results at all times. Thus, the results achieved could be validated, and any desired changes and adjustments could be quickly adopted. In an iterative process, the objectives, methods and analysis results were continuously coordinated with the city of Olfen as the addressee. In addition, two expert workshops for interim results and investigation priorities were held during the analysis. Within the city administration, the involvement of municipal drainage operation, civil engineering, urban development and planning as well as the fire department was an important part of the pluvial flood risk analysis. Expert reports and data on pumping operations by the fire brigade, central overflow points or statements on planned residential areas could be included in the analysis and thus qualify the analysis. In the course of the collaboration, it was also possible to improve the validity and accuracy of the results. Furthermore, already during the analysis phase, individual results could be incorporated into ongoing processes, e.g., the wastewater disposal concept or legally binding land-use planning, which shows that the results could be used for future planning decisions. Finally, all results were presented to and have been proven by the local political assembly.

3. Results

The determined hazard values of the topographic analysis are presented as average water spreading volume in m$^3$ per m$^2$ building block. On the one hand, the results reflect the topographic conditions; on the other hand, the influence of urban structures, building types and density on urban precipitation runoff is already apparent. By means of this procedure, areas (building blocks) can be determined which should be given special consideration because of their hazard, since high water spreading volumes are reached there. This concerns, for example, the central sink in the south of the city centre (shown in red in Figure 3 hazard map).

These results take on particular significance in combination with urban vulnerabilities, since this is where, for example, school locations and residential and care facilities for the elderly are affected. Particularly sensitive groups of the population and facilities worthy of protection may be affected, so that it is advisable to consider individual buildings and infrastructure. For this purpose, hazard profiles were drawn up for all social and critical infrastructures in Olfen. The numbered buildings in Figure 4 show a church institution (1), a primary school (2) and a retirement home (3). All three facilities are located in a large area with a high to very high hazard value. In some places, water spreading volumes from max. 50 cm (church facility) up to more than one metre (retirement home), even directly at the building structure, can occur. This means that the accessibility of the facilities can be severely
restricted in the event of heavy rainfall. In addition, high flow velocities of up to 0.75 m/s need to be expected. The hazard profile shown here is a particularly affected hotspot in the city of Olfen. Due to the concentration of highly sensitive infrastructures in this area, it is recommended to adapt the current utilisation concepts to the expected effects of heavy rainfall.

**Figure 3.** Overview of the resulting maps: (top) heavy rain hazard map; (center) damage potential map; (bottom) population sensitivity map.
The results are also relevant against the background of the particular hazard, respectively, the vulnerability of buildings and infrastructures, which were considered on the basis of damage potentials. Due to the high resolution of the data at building block level, in some places, a causal connection between the age classes of the buildings and the potential damage can be seen. For example, the relatively newly built residential areas in the south-western part of the city have a predominantly lower damage potential than the building blocks of older residential areas. The combination of the damage potential and the vulnerability finally results in a risk map (see Figure 5).

Figure 4. Detailed heavy rain hazard profile.

Figure 5. Pluvial flood risk index for the city of Olfen.
The pluvial flood risk map can be used to identify areas, buildings and infrastructure or population groups that are particularly at risk. This allows statements to be made on the potential extent of danger to life and limb and damage to public buildings and infrastructure facilities. Thus, it is possible to spatially explain the relation between the various risk components. The comparison of the maps in Figure 3 illustrates that even if the hazard value is low, the value of the final risk can be high according to a high vulnerability of the building block due to, e.g., particularly sensitive groups of the population living there or a high potential damage. For example, the small bungalow park in the north (see Figure 5, red square), for which a high risk of heavy rain has been determined, on the one hand, has a low hazard level but, on the other hand, this building block is highly vulnerable, since both the damage potential and the sensitivity of the population are relatively high.

4. Discussion

The pluvial flood risk analysis is an important component within the heavy rain risk management (for Germany, see, e.g., [35,54,55,57]). This underlines the importance of integrated and comprehensive spatial risk assessment approaches to be able to adequately react to heavy rainfall events with adaptation strategies and measures in the course of urban development. The aim of the present urban pluvial flood risk analysis was to identify and analyse particularly affected areas/building blocks for small and medium-sized cities in the event of heavy rainfall. The results of our case study are regarded as an integral part of the evidence basis for an integrated spatial development concept. The necessary delineation of the area is essentially carried out on the basis of the determined pluvial flood risk, which is taken into account in addition to other urban development deficiencies. Furthermore, it is shown that the pluvial flood risk is also negatively influenced by structural, building and technical conditions (e.g., year of construction or building services in the basement), which are mainly to be found in existing building stock from the 1960s and 1970s. These neighbourhoods and residential areas are at the same time prioritised urban renewal areas that are to be renovated in the future. The results of the analysis have thus formed the evidence basis, which made it possible to concretise the urban development deficiencies in accordance with the overall objectives of urban development and, specifically, a strengthening of resilience, which the city aims to achieve. Potentially affected areas, public facilities and infrastructures need to be identified first. Only on this basis, recommendations for action, strategies and measures can then be derived to reduce and prevent damage and/or the functional failure of important infrastructures in the event of an incident [55,57–59].

The discussion about possible effects of climatic changes on heavy rainfall intensities and their frequency in the future, as well as the annual reports on pluvial flooding caused by heavy rainfall and urban flash floods, has already had an impact on urban planning and urban drainage in Germany [35,57]. Methodologically speaking, flood hazard analyses are an important evidence basis for urban development processes and a central element of comprehensive heavy rainfall risk management. Both the preparation of spatial analyses and the handling of corresponding results (e.g., an evaluation of the identified risk) in the near future are important tasks not only for planners but also for decision-makers, city administrations and drainage experts [10,22,35]. On the one hand, the methodological approaches for conducting heavy rain hazards analyses are already established in Germany [35], but on the other hand, not every approach can be easily transferred to every city or consider the vulnerability component properly. Thus, the required and available database, the natural location or topographical conditions (physio-geographically), the development of the population and settlement area or, last but not least, the size of the city must be taken into account (e.g., [17,20,57]), but the necessity for integrated assessment which considers the given factor of vulnerability must not be questioned. The results depend on the chosen research objective, which helps to identify hazard areas, evaluate risks and develop and implement appropriate measures and action plans. The purpose of the analysis to be defined in advance naturally has a considerable influence on the selection and preparation of the data basis and indicators at all levels of the analysis. This has also been shown by the cross-analysis of comparable studies and research.
Despite the numerous and comprehensive guidelines, technical working aids and leaflets on pluvial flood risk management and flood prevention and protection in general, current risk analyses sometimes differ considerably. This applies, for example, to the basic data, the accuracy of detail or, in particular, the components of vulnerability taken into account. We have therefore designed our analysis approach in order to provide the same level of detail for all components of the analysis. Especially for the components of vulnerability, we wanted to assess them not only in terms of potential economic damage (physical) but also in terms of existing sensitivities of the exposed population (social). Nevertheless, as [22] have already pointed out, the mere consideration of damage estimations to describe the economic dimension of vulnerability must be seen critically, as this does not automatically mirror the economic losses which could also be caused by indirect effects elsewhere. Due to a lack of comprehensive data regarding the expected losses, in practice, a specific consideration of the economic dimension beyond the damage potentials is often not possible. Moreover, in our analysis, we were only able to focus on the damage potential as a partial illustration of the economic dimension because of the reasons mentioned above. However, in the case of the availability of a more comprehensive data basis, the consideration of several variables for an approximately adequate representation of the economic losses is strongly recommended.

The cross-analysis of the literature and the results of our analysis show the importance and influence of social vulnerability. Most studies already take into account characteristics such as age, level of education, health condition (e.g., pre-existing illness) or physical abilities (e.g., swimming skills) and thus go beyond the consideration of the absolute exposed population. Furthermore, only the status quo is usually recorded and mapped. A consideration of the future population development, the advancing urbanisation trend or related land use changes has rarely been presented so far. While, in the current discussion about urban flash floods and pluvial flood risks, climate change is widely discussed as a major driver of future risks, the discussion lacks other relevant drivers which determine a future risk. In addition to land use change, the main drivers of future risk are changes in the composition and quantity of the population. Therefore, it is particularly important to also take changes in the land use patterns into account in a parallel modelling of climatic and societal changes [60]. Additional research is needed here in order to further qualify the corresponding results of hazard and vulnerability analyses and pluvial flood risk assessment.

5. Conclusions

Small and medium-sized cities in particular are still faced with the challenge of carrying out comprehensive analyses of the risk of heavy rainfall with limited financial and personnel capacities and the often inadequate data basis and lack of familiarity with state-of-the-art methods. The municipal administrations are often not sufficiently trained to judge the validity of the output of engineering services. The analysis approach presented is applicable by cities of similar size in various countries. The step-by-step explained methodological approach empowers municipalities to either carry out their own analyses with the available resources or to properly commission and support external engineering services in a targeted and appropriate manner.

The presented pluvial flood risk assessment aimed at the identification of pluvial flood risk hotspots on a citywide scale. The use of a scientifically proven, spatially-specific increase factor for the impact of climate change on extreme events in combination with the inclusion of foreseeable land use changes enables municipalities to proactively adapt to a potentially worsened future baseline trend. The consideration of concrete physical and social aspects allows a detailed look at spatial characteristics that influence the pluvial flood risk and goes beyond a pure hazard analysis. Only on this basis, concrete adaptation requirements can be determined and transformed into priorities for action by weighing these requirements against other concerns and interests which play a role when setting up land use plans. This implies that the results achieved must be subjected to a final evaluation, which then enables the decision-makers and the city administration to define, for example, concrete protection goals for individual buildings and infrastructures. This political–normative process transfers the factual
level into a value level. At the end of the risk evaluation, the following question remains: where am I willing to take a certain amount of risk and where is even the smallest amount of risk unbearable?

Further research is needed in regard to the indirect effects of service disruptions caused by pluvial flooding. Municipalities are entitled to govern their own territory only, which automatically limits the ability of urban actors to consider these kinds of effects, which may cause impact elsewhere in other regions.

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