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# Flood-related fatalities during the flood of July 2021 in North Rhine-Westphalia, Germany: what can be learnt for future flood risk management?

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## Abstract

During the severe flooding in July 2021 190 people lost their lives in Germany, which is the highest number of flood-related fatalities since 1962. 49 people died in the densely populated state of North Rhine-Westphalia (NRW), whose flood risk management has, however, often been regarded as pioneering in Germany. To further improve flood risk management in NRW, the causes and circumstances of all 49 flood-related deaths were analyzed. Based on official files a structured document analysis was performed and a new coding scheme was developed that relates accident locations and victims' activities to accident dynamics and causes of death. Circumstances and causes of death differed significantly between in-/outdoor accidents, age groups, and areas with different event magnitudes. Elderly people (>60 years) were particularly at risk; they account for two thirds of the dead. Eight of the 25 people who died in a building were surprised by water entry into their apartments. In addition, there are indications that nine of 24 people who died outdoors were surprised and caught by water on their way home or when trying to leave the flooded zone. Hence, it is assumed that a lack of warning played a role in around one third of the cases. In most of the remaining cases, hazards were underestimated pinpointing to insufficient awareness and weaknesses of crisis and risk communication. 14 people died in their basements while attempting to inspect equipment (e.g., pumps) or to inspect, minimize, or repair damage. Since property-level adaptation has been emphasized in flood risk communication, life-threatening situations during fast onset-flooding and the priority to be safe have to be emphasized in future communications. It has to be acknowledged that the official hazard maps indicated no risk from flooding at around half of the 49 accident locations illustrating the exceptional event magnitude and shortcomings of existing hazard maps. Still, warning levels and flood hazard maps should be better linked to identify hazard zones and to enable appropriate behavior including (self-)evacuation.

### Keywords

flood fatalities, warning, risk communication, NRW

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# 1 Introduction

On 14 July 2021, the depression "Bernd" brought very intense rainfall to Western Europe, which was found to be extreme across multiple spatial and temporal scales (Lengfeld et al. 2023) and led to severe flooding, even on smaller watercourses and streams. In Germany, the federal states of North Rhine-Westphalia (NRW) with the catchment areas of the rivers Erft, Rur, Ruhr and Wupper and Rhineland-Palatinate (RP) with the catchment area of the river Ahr were particularly affected (Kron et al. 2022; see also Fig. 5). The rivers Ahr, Erft and Rur originate in the Eifel and showed the highest discharges. For example, return periods of the discharge of river Ahr in RP were estimated to exceed 1000 years at the gauge Altenahr by far (Vorogushyn et al. 2022). However, flood peaks were not just caused by the amount of water, but were due to backwater effects at clogged bridges. In fact, Dietze et al. (2022) illustrate how the floodwaters eroded and altered the landscape and carried wood, sediment, and debris which aggravated loss and damage in many places. Altogether, the floods destroyed and damaged several thousands of buildings and important infrastructure such as transportation, power, telecommunication, water supply and sewage systems (e.g., Koks et al. 2022). Disaster funds of €30 billion have jointly been provided by the federal and state governments of Germany to help the affected areas rebuild. Not only is this high amount of financial damage unprecedented in the recent past, unfortunately the humanitarian impact of the flood was extraordinary as well: 190 fatalities were reported from all over Germany, thereof 49 people from NRW and 136 from RP, with, however, some uncertainties in the data (Table 1); one person is still missing even two years after the event. According to the HANZE database (Paprotny et al. 2018) and own searches, only the storm surge of 1962 with at least 347 deaths along the German North Sea coast, thereof 318 in the city of Hamburg, has claimed more deaths due to flooding since 1870 in Germany. By comparison: in the floods of August 2002, which had in the Saxon Ore Mountains (*Erzgebirge*) similar hydrological and hydraulic characteristics to the event of July 2021, 21 people lost their lives.

Table 1: Fatalities caused by the flood event in July 2021 in Germany per federal state (as of June 2023; data basis: media reports and own research).

| Location of the Federal State | Name of Federal State | Number of people killed by flooding in July 2021 | Remarks |
|---|---|---|---|
|  | Rhineland-Palatinate (RP) | 136 | thereof nine people residing in NRW and one person from Lower Saxony (NI); 135 people died in the Ahr river catchment, one person in the region of Trier |
| | North Rhine-Westphalia (NRW) | 49 | thereof one person residing in RP; note that (at least two) deaths after evacuations were declared natural and hence not counted* |
| | Bavaria (BY) | 2 | among them probably one natural death* |
| | Saxony (SN) | 2 | among them one person that died a week after "Bernd" due to local flooding |
| | Baden-Wurttemberg (BW) | 1 | on 12 July 2021 due to high water levels in the river Jagst |
| | **Total** | **190** | |
| | Missing people | 1 | one resident from Berlin (B) is still missing in RP |

*: In Germany, the medical certificate of cause of death (MCCD) distinguishes among other things between a natural, unnatural and unclear manner of death. This does not necessarily describe the medical cause of death, but reflects the circumstances of the death. It is primarily a legally relevant term, as unnatural or unclear deaths initiate an investigation by a coroner and/or public prosecution. Rothschild (2005) recommends certifying an unnatural death whenever there is an indication for it; this includes all kinds of accidents, suicide or indication for homicide. A natural death can be certified if a doctor knows that the patient died from an internal medical reason, without a directly or indirectly preceding legally relevant event (Rothschild 2005).

In contrast to Rhineland-Palatinate, where the highest flood magnitude and all fatalities except for one person occurred in the valley of the river Ahr, there was more widespread flooding in NRW impacting several districts in July 2021 implying that fatal incidents might be more diverse. Therefore, this paper aims at analyzing causes and circumstances of all 49 fatalities in NRW in order to derive recommendations for future flood risk management.

NRW is regularly hit by river floods, particularly along the river Rhine with severe floods e.g., in 1983, 1988, 1993 and 1995 causing financial damage, particularly in the city of Cologne, but only few fatalities. Although consistent and regional data on flood fatalities are missing in Germany, the so-called “Heinrichsflut” on 15/16 July 1965 was probably the most fatal event in NRW until July 2021 with 16 fatalities in total, thereof nine in NRW. These events triggered improvements and changes in flood risk management, e.g., with regard to water retention, governance and warning. Further, the floods of 1993 and 1995 led to a German-wide shift toward more risk-based and integrated flood risk management approaches (LAWA 1995; Bubeck et al. 2017). In fact, the first publicly accessible flood hazard maps and quantitative risk assessments were published for the river Rhine in NRW (MURL 2000; ICPR 2001).

In recent years, pluvial floods hit several cities across NRW, e.g., Dortmund in 2008 or Cologne in 2017. In July 2014, the city of Münster was severely hit resulting (back then) in the highest amount of insured flood losses caused by pluvial flooding in Germany (e.g., Spekkers et al. 2017); two people died (pers. comm. with the former head of the fire brigade of the city of Münster on 28 June 2022). Initiated by such events, guidelines for assessing risks from pluvial floods were released in NRW (MULNV 2018) and the development of local pluvial flood hazard maps and respective risk management strategies has been funded by the state of NRW, which is also regarded as a pioneer in respect to climate change adaptation (King 2022).

The high number of fatalities in July 2021 fundamentally questions flood risk management in Germany, particularly in the most affected federal states, and calls for a detailed investigation. Risk and crisis communication including the warning system are of main interest (Cornwell 2021). Generally, in natural hazard processes such as flooding, it is the primary goal of warning systems to avoid fatalities by enabling people in flood-prone areas to get to safety in due time or by officially evacuating areas at risk through disaster management. However, warnings are only successful if they reach the people at risk, who interpret the warning correctly and act adequately (Penning-Rowsell and Green 2000). During the flood of July 2021, warning processes were insufficient: in NRW, 35 % of people in affected areas reported that they had not been warned (Thieken et al. 2023). Furthermore, of those who had been warned, around 50 % did not know how to behave adequately. A majority of 87 % was surprised by the actual flood magnitude since based on the warnings only 15 % had anticipated a severe flood with high impacts (Thieken et al. 2023). Therefore, the question arises whether shortcomings in the warning processes contributed to the high number of flood fatalities and what this implies for an improvement of the warning system and crisis communication, i.e., the dissemination of warning messages with corresponding recommendations for action. For example, analyses of flash floods in the US from the 1970s revealed that people who are in danger of flooding in V-shaped valleys should directly walk or climb to safe places uphill instead of leaving the valley by car on the roads (Gruntfest et al. 1978). Analysis from France (Vinet et al. 2012), England (Lumbroso and Vinet 2011) and Greece (Diakakis and Papagiannaki 2021) revealed that many people drowned in one-story buildings since there was no way to evacuate vertically, e.g., by escaping on the roofs. Hence, ensuring that there is an accessible vertical evacuation route, also termed “shelter-in-place”, is a life-saving building code in areas prone to flash floods where timely evacuation is often constrained due to short lead times (Haynes et al. 2009). In addition, better forecasting and warning in flash flood areas is requested (Vinet et al. 2016).

Generating flood hazard and risk awareness and informing people about suitable protection and precautionary strategies is the task of risk communication, which is supplemented in case of an upcoming event by crisis communication. In fact, next to the examples mentioned above, analyses of flood fatalities in industrialized countries (Europe, USA, Australia) have already revealed important insights into risk-taking behaviors and entry points for improved communication (e.g., Jonkman and Kelman, 2005). For example, since vehicle-related fatalities are an important fatal pathway, e.g., in the US (Kellar and Schmidlin 2012; Han and Sharif 2020), blocking roads and preventing people from driving into flooded areas is an important issue in many countries and should already be addressed at driving schools (e.g., Han and Sharif 2020; Petrucci 2022). These examples demonstrate how an analysis of the circumstances that led to fatalities can help improve flood risk management. However, cases analyzing flood-related fatalities for particularly fatal events are still scarce (Jonkman et al. 2018), although their insights could contribute to achieving the first target of the Sendai Framework for Disaster Risk Reduction 2015–2030, i.e., the substantial reduction in global disaster-related fatalities per 100 000 people by 2030.

Analyses of flood fatalities with the goal to improve flood risk management are often hampered by a lack of data or a lack of detail, e.g., when data are available on an aggregated level only. This usually does not allow us to investigate the specific circumstances, which are needed to understand why an accident led to a fatal outcome and to recommend interventions. For this study, official documents from a parliamentary investigation, including death investigation files, were provided and enabled an in-depth analysis. Structured text analyses were combined with a new coding scheme that better relates accident locations and victims' activities to accident dynamics and causes of death than existing approaches. This paper will introduce the approach and learnings from the event of July 2021 in North Rhine-Westphalia based on Thieken et al. (2022).

# 2 Data and methods

## 2.1 Data sets

In the framework of an authorized parliamentary investigation on the flood in 2021, two encrypted hard drives with numerous documents from the North Rhine-Westphalian Ministry of the Interior (IM) and the North Rhine-Westphalian Ministry of Justice (JM) were provided, respectively. In particular, the IM data challenged the analysis, since data totaled 112 gigabytes (GB) with more than 2700 numbered PDF, audio and video files. However, it also included a first overview table on the official 49 flood fatalities in NRW with basic socio-demographic information, which served as orientation in the subsequent research. The JM data contained 3.53 GB and approx. 380 files, among which were the public prosecutor's investigation files (death investigation files) on 46 of the 49 deaths under study including police communications and documentations of the accident locations, reports from eye-witnesses and in most of the cases an autopsy report.

As additional information, hydrological data, cross-sections, reports, presentations and media information on the flood in July 2021 were provided by the North Rhine-Westphalia State Office for Nature, Environment and Consumer Protection (LANUV) and by water associations (Erftverband, Ruhrverband and Wasserverband Eifel-Rur – WVER). As complementary source of information a media search in the online press archive of GBI-Genios Deutsche Wirtschafts-datenbank GmbH on fatalities during the 2021 flood (search period: 14th July 2021 to 31st December 2021) was performed. Furthermore, official population statistics from the GENESIS online database of the German Federal Statistical Office (Destatis 2021) were used to compare socio-demographic information of the fatalities with the general population of NRW. Moreover, accident locations were searched in the flood hazard maps of NRW's water information system ELWAS. The maps were produced in 2019 as part of the second implementation cycle of the European Floods Directive (2007/60/EC). In addition, geographic information, i.e., the water network as well as pedological and geological data from the NRW Geoportal, as well as shape files with administrative boundaries (VG250) and a digital elevation model (DGM200) from the Federal Agency for Cartography and Geodesy (BKG) were used. Finally, warnings provided in July 2021 via the modular warning system MOWAS by the Federal Office of Civil Protection and Disaster Assistance (BBK) and data from an online survey on the warning situation in July 2021 in the affected areas (Thieken et al. 2023) were considered to better understand the warning situation.

## 2.2 Workflow

The main methodological challenge was to search the large volume of IM data for relevant information on the flood-related fatalities and to retrieve it in a structured way. Therefore, the workflow depicted in Figure 1 was developed.

First, the IM data were analyzed by means of the software AntConc (version 4.0.4), a freely available software for linguistic research. All PDF files were loaded into the software, which extracts text passages automatically and stores them in a locally saved database. Then the tool Key-Word-In-Context (KWIC) was used to search all documents in the database for a number of keywords defined for the study at hand (*: wildcard): disaster*, *died*, drowned*, exitus, corpse*, victim*, electrocution*, death*, lethal*, fatal*, dead*, accident*, injured*, and missing* (in German: **glück**, **starb**, **storben**, *ertrunken**, *exitus*, *leiche**, *leichnam*, *opfer**, *stromschlag**, *tod**, *tödlich**, *tot**, *unfall**, *verletz**, *vermisst**). The KWIC-tool displays a list of results and shows for each hit 10 to a maximum of 25 words that precede or follow the keyword. Identical or very similar text passages are listed directly one below the other, i.e., the hits are ordered according to their frequency. The PDF file in which the hit was found is also reported. By this approach, the multiple redundancies in the IM data could be easily recognized and relevant text passages were systematically identified. These were copied word-by-word to a list of results in an Excel file, next to its source. If the 25 context words were not sufficient to understand the context of a relevant fact, the corresponding text passage was searched in the original PDF file and a longer text passage was added to the list of results. In addition to the IM data, newspaper articles from a keyword search in the database GENIOS were analyzed in the same manner, whereas video and audio files of the IM data were neglected. Since some PDF files caused an error when imported to AntConc, these files were searched individually with a reduced keyword list (i.e., exitus, corpse, death*, fatal*, dead*) using the search function in Adobe Acrobat Reader. The files of the JM data were evaluated individually, as these prosecution investigation files presented all information on the individual deaths. Data files that were not relevant to the investigation of the flood fatalities were not considered further.

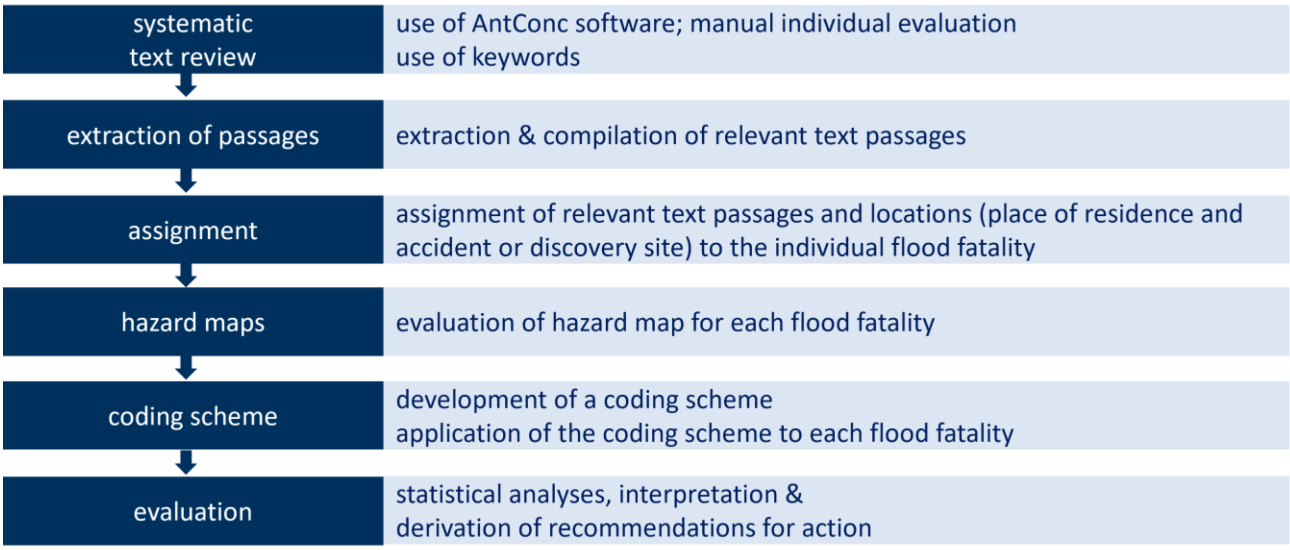


Figure 1: Workflow of data processing.

Each text passage in the list of results was assigned to the individual flood victims by means of a unique identifier (ID) on the basis of the information contained therein (e.g., locality, socio-demographic information). In a next step, a spreadsheet was created for each deceased person and all associated text passages were compiled per case.

Since personal details of the victims were not blacked out in the JM records, it was ultimately possible to determine the exact age and place of residence for (almost) all of the deceased, which facilitated the assignment of contextual information to each case. In order to determine whether an accident site was located within a flood hazard zone, each address of an accident site was searched in NRW's flood hazard maps (ELWAS, see above). For this, the maps for an extreme flood scenario were chosen; the maps contain, among other things, information on possibly inundated areas and water depths expected during an extreme flood event. The definition of the extreme flood scenario has not been harmonized in Germany by now (DKKV 2015). In NRW, this extreme scenario reflects a flood that occurs on average significantly less frequent than every 100 years (i.e., every 1000 years, so-called "millennium floods") (Ministry for Climate Protection, Environment, Agriculture, Nature and Consumer Protection of the State of NRW, n.d.). For each case, a screenshot of the map was copied to the Excel file.

The collected information on each case was finally analyzed in a structured way with the help of a coding scheme. For this study, a new coding scheme was developed to account for the high level of detail of the data and to better link the circumstances of flood-related deaths to recommendations for flood risk management. The scheme was inspired (deductively) by the international literature (e.g., Jonkman and Kelman 2005; FitzGerald et al. 2010; Badoux et al. 2016) and European databases (Petrucci, Aceto et al. 2019; Petrucci, Papagiannaki et al. 2019), but was adapted (inductively) to the data at hand. The whole coding scheme is provided in the Appendix as Excel file that can be used as a template for future studies. The main variables are an individual identifier of each fatality (ID), gender and age (in years) of the fatality, previous illnesses or mobility impairments, place of residence of the victim, general description of the accident location (bridge, cellar, street, etc.), address of the place where the body was found, municipality of the place where the accident occurred (or – if unknown – place where the body was found according to official police reports), official municipality ID, county of the place where the accident occurred (or – if unknown – where the body was found), official county ID, geographic sub-area (if applicable, see results section), time of the accident (assuming light from 5 a.m. to 10 p.m. and darkness between 10 p.m. and 5 a.m. in July), chronological classification of the accident with regard to the event (pre-impact; impact; post-impact), indication whether the accident site is in- or outside the flood hazard zone according to the extreme flood hazard map of 2019, water level class at accident site according to the extreme flood hazard map of 2019, classification as to whether the person was a resident at the site of the accident, a non-resident or a (resident) rescue worker, locality of the accident as indoors or outdoors, detailed location of the accident (e.g., basement, ground floor, in or near a vehicle), victim's activity in the context of the accident (e.g., asleep or indoors surprised by the event), accident dynamics describing the fatal pathway (e.g., trapped/entrapped in a flooded room; bridge collapse and then swept away by water and trapped or injured by objects/floating debris in the flooded area), and medical cause of death (e.g., drowning, injury (polytrauma); internal cause such as heart attack, stroke or similar). Recommendations for flood risk management were added as open text since it was difficult to provide predefined categories for this. With a broader data base categories could be added in future.

The coded variables were finally used for statistical analyses performed with the help of the software SPSS and Excel as well as for spatial analyses in the geographic information system QGIS. Since the variables are predominantly categorial, i.e., represent different, mutually exclusive categories, simple descriptive statistics, especially frequency analyses, were used. In order to assess whether one frequency distribution deviates statistically significantly from another, the chi-square test can be used at this data level, but has only limited significance given small sample sizes. In particular, it was tested whether the medical causes of death, timing, detailed locations and flood hazard zones of the accidents, the victims’ activities and the accident dynamics differed between in- and outdoor cases (see section 3.1), gender and age groups (see section 3.2) as well as different geographic sub-areas that reflect differences in event magnitude and landscapes (see section 3.3).

# 3 Results and Discussion

For potential improvements to risk management, the locations and contexts in which the fatal accidents occurred are of particular relevance next to event characteristics and socio-demographic information. Before (significant) differences in these regards will be studied for different subsets, accident locations, victims’ activities, accident dynamics and medical causes of death will be presented for the whole data set.

## 3.1 Overview of accident locations, dynamics and consequences

The accident locations revealed that 25 people died indoors and 24 outdoors. In the buildings (Figure 2), about half of the people died in their basements (13 people). In addition, two people drowned in basement apartments. Furthermore, seven people died in their apartments on the ground floor, two more on an upper floor and one person in a non-residential building. The outdoor cases are characterized by the mode of transportation in Figure 2: eleven people were driving or were near their vehicle when they were caught by the floodwater; the other 13 people walked outdoors on a road or in open terrain.

Figure 2 reveals that death by drowning was responsible for the majority of cases (i.e., 33 cases or 67.3 %). In three other cases, death was due to a combination of suffocation and drowning (as a result of being trapped under a car in a flooded area or by a lack of oxygen in a basement, which led to unconsciousness and drowning). In two other cases, death by suffocation as a result of inhaling mud or due to the weight of a heavy object on the chest was certified. The cases mentioned so far and a further one, in which vertebral fractures with spinal cord injuries (polytrauma) were identified as cause of death, can be attributed to the direct physical impact of the floodwater on the victims. In contrast, the following deaths were caused by the flood, even if there was no or only little contact with water: One case with polytrauma can be attributed to a traffic accident, which is to be considered an indirect but immediate consequence of the flood event. In seven cases, internal medical causes of death were found, usually heart attacks or similar, which can be traced back to overexertion, excessive demands or shock. In addition, two people died from massive burns since a flood-damaged oil heating caught fire, which was considerably aggravated by an oxygen cylinder (for a respirator) located in the hallway of the building.

The differences in the medical causes of death are weakly significant ($p \leq 0.1$) between indoor and outdoor accidents and are mainly due to the fact that drowning occurred more frequently in outdoor accidents than in indoor accidents (see

Figure 2). In contrast, more internal medical causes (heart conditions) were found responsible for deaths indoors. Death due to polytrauma (in two cases) occurred exclusively outdoors, while two deaths as a result of burns occurred only indoors.

Figure 2 further links the locations of the accidents with the medical causes of death via the activity of the deceased and the accident dynamics. Each line in Figure 2 represents one person, but similar cases were clustered as indicated by the numbers. This grouping results in various fatal pathways that might serve as starting points for better risk management. Since the activities of the fatalities and the unfolding accident dynamics naturally differ between indoor and outdoor cases, Figure 2 presents indoor cases in the upper part and outdoor cases below. Moreover, the chi-square tests are highly significant ($p \leq 0.001$) with regard to the activities and accident dynamics in buildings and outdoors.

Indoors, most fatalities (14 people) were checking their property-level flood adaptation measures (e.g., pumps) or were checking, removing or trying to reduce flood damage. This mainly took place in basements or in basement flats. However, Figure 2 illustrates that these people were not necessarily trapped in the basement due to a water ingress, even though these tragic cases (five in total) occurred, some with very dramatic, but futile rescue attempts. Four deaths were due to domestic accidents, mainly falls in slightly to moderately flooded basements, after which the victim was unable to get up again. In three other cases, death was due to internal medical causes and thus rather triggered by being overburdened by the situation or by carrying out emergency measures. In two cases, high levels of carbon dioxide and a correspondingly low level of oxygen, probably caused unconsciousness, which led to drowning in a moderately flooded basement.

Furthermore, ten people were surprised in their flats (in one basement apartment, several apartments on the ground floor and one flat on an upper floor) by the water ingress or the triggered flat fire (see above), whereby the documentation for two people suggests that they had been warned in advance, but underestimated the magnitude of the unfolding event and were then surprised by the water ingress. Seven people were trapped in a flooded room after the water ingress or were entrapped without escape by falling objects. In one (preconditioned) case, the water ingress led to heart failure. Two people were incapacitated as a result of a fire (see above). In this case, escaping to higher floors did not help either. In contrast, vertical evacuation was documented as a successful strategy in severely flooded homes also in vicinity to locations of fatal incidents.

Of the eleven people who were travelling in a vehicle (nine cars and two fire brigade vehicles), one person was found drowned while still wearing a seat belt in the vehicle. Another person suffered a traffic accident in a road closed due to the flood and succumbed to the injuries a few weeks later. A third person suffered a fainting spell while driving (as a passenger) and died despite resuscitation. A fourth person got stuck while boarding a vehicle, was swept away by a flood wave, pushed under water and subsequently drowned. In case of seven people, it was (partly) observed or must be assumed that they lost control of their vehicle in the flooded area or that the engine failed. They were still able to leave the vehicle, but lost their stability in the water current and were swept away. The locations where the bodies were found and their injuries suggest that some of them were transported several hundred meters through the water away from the accident site. Many bodies which were found in the open, were only scantily clothed or completely unclothed, which underlines the very strong currents and danger of the flood.

Finally, 13 people died while being outdoors on foot. Two of them were involved in private rescue operations; in the case of another two people, it must be assumed that they ignored warnings or safety instructions and underestimated the hazard. In the end, both failed in their attempt to leave the hazard zone and were swept away by the water – as was another person who was swept away by the water when leaving their house and was later found dead in the garden. In the case of three other pedestrians, the reason why they were outdoors is unclear, while in six other cases it is documented that the now deceased were on their way home after work or after visiting family members, or were seeking a safe place at a family member because their own home was already flooded. Three of these (very young) people were swept away by a wave when crossing a river on a bridge; in two cases this was associated with a bridge collapse (Figure 2).

It should be noted that most of the fatalities (40 people and four rescue workers) were local residents, i.e., died at their place of residence. Four people were traveling by car in places where they did not reside; one person died at his place of work. However, of the non-residents just one person was registered outside the affected areas in NRW, namely in Rhineland-Palatinate. The question arises to what extent these deaths could have been (partially) prevented by appropriate risk communication using the official flood hazard and risk maps. Such knowledge could have influenced decisions to evacuate, i.e., to leave the flooded area in advance and based on corresponding warning information.

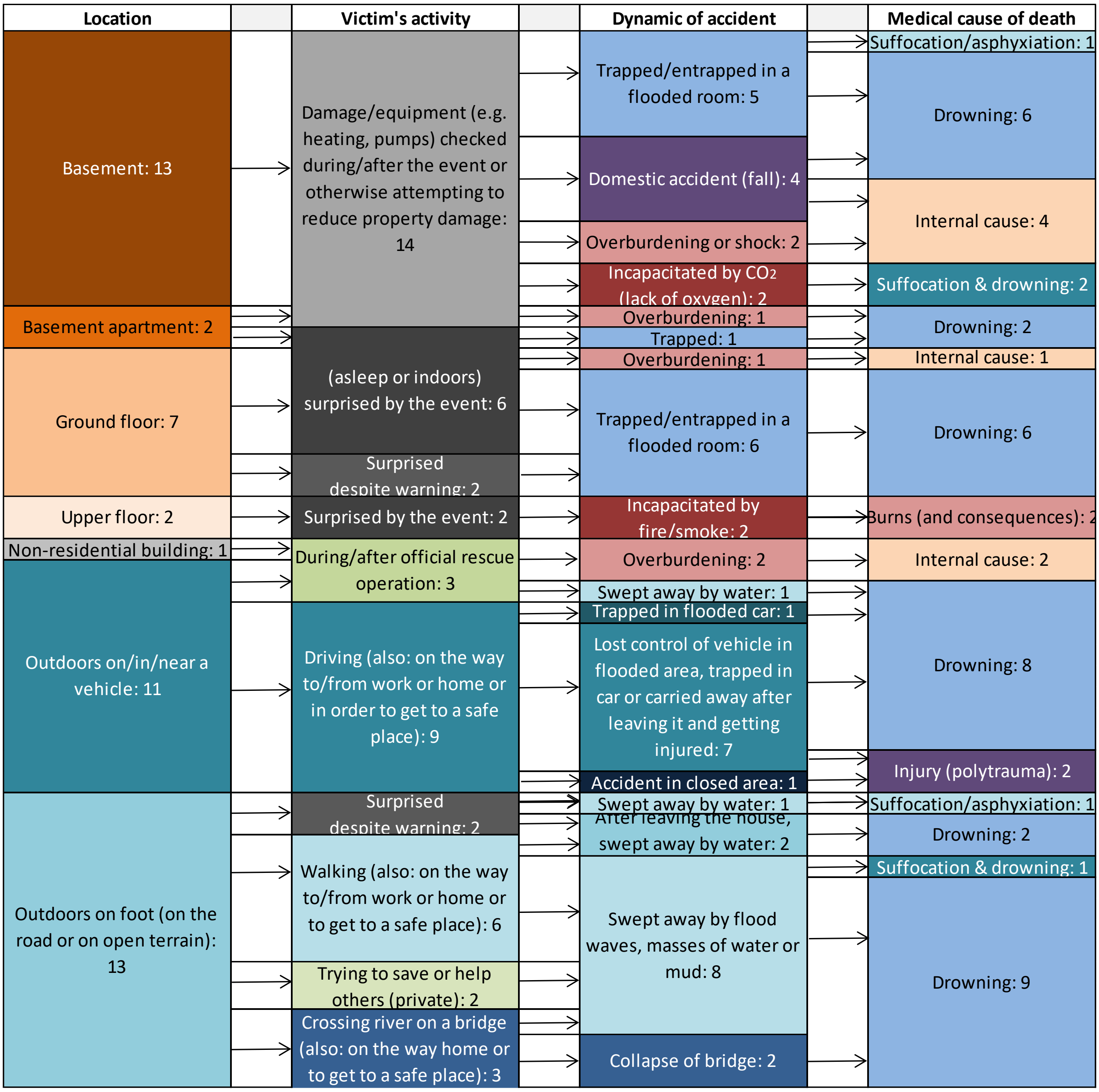


Figure 2: Locations of the fatal incidents, victim's activities, accident dynamics and medical causes of death of 49 flood-related fatalities in North Rhine-Westphalia (NRW) in July 2021. Note that each line initially represents one person, but similar cases were merged as indicated by the numbers following the item descriptions.

The hazard maps for NRW are publicly accessible and allow an address-specific search for the locations where the accidents occurred. As mentioned in section 2, the representation of the accident sites in the hazard maps was searched for all cases – with the exception of three official rescue operations and one missing address. Since the location of the accident is often not known exactly in the cases where people died outdoors, the search results are presented differentiated between in- and outdoors: for ten buildings in which people lost their lives, the flood hazard maps of 2019 show no inundations for an extreme flood scenario (return period of around 1000 years). In nine cases, a low flood hazard (with water depth up to 0.50 m) and just in four cases a higher flood hazard with inundation depth of up to one meter above the ground surface are depicted in the maps. The outdoor accident sites show a similar pattern: at 14 sites no flood hazard zone is indicated; at six sites water depths up to 0.50 m and at two sites up to 1 m are shown. These findings clearly indicate that the flood hazard maps (with artificial, but extreme scenarios) did not adequately depict the extreme event of July 2021. This is partly due to the high event magnitude, e.g., small streams were occasionally reported to swell from <1 m in width to several meters.

In summary, Figure 2 reveals that eight of the 25 people who died in a building were surprised by water entry into their apartments. In addition, there are indications that nine of 24 people who died outdoors were surprised and caught by water on their way home or when trying to leave the flooded zone. It is assumed that a lack of warning played a role in these 17 cases, i.e., the eight people caught by surprise indoors and the nine people who died outdoors on their way home or while trying to leave the flood zone (too late), who make up a third of the fatalities. As shown by Thieken et al. (2023), the dissemination of warnings and behavioral recommendations revealed many deficits in July 2021. The proportion of people from NRW who reported that they had not been warned (i.e., 35 %), is similar to these fatal accidents.

In most of the remaining cases, hazards were underestimated pinpointing to insufficient awareness and weaknesses of crisis and risk communication. Figure 2 highlights that one important dangerous location are basements, followed by being outdoors on foot or driving. This is basically in line with similar studies (e.g., FitzGerald et al 2010; Badoux et al. 2016; Vinet et al. 2016). However, the diversity of accident dynamics is presented clearer in this study and provides crucial insights for risk communication, e.g., the importance of domestic accidents or the mechanisms of vehicle-related accidents to be addressed at driving schools.

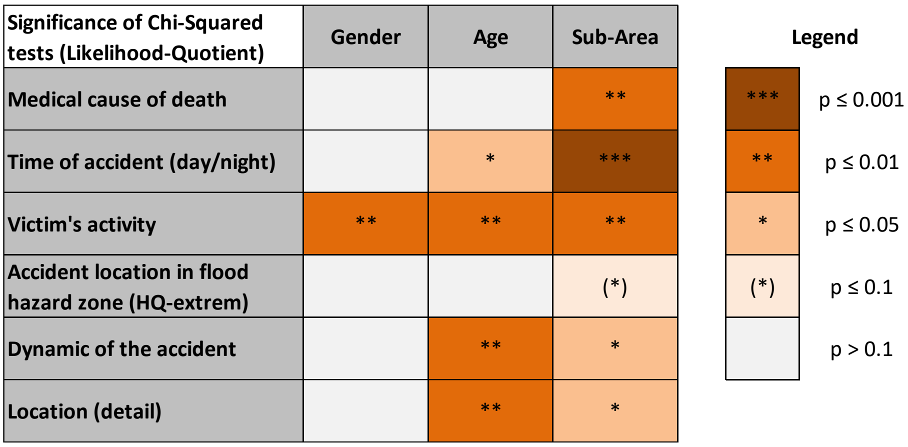
Even if the international literature had not been studied, official flood risk managers could have known some essentials from other flood events in NRW. A closer look at the two men who were killed by the pluvial flood event in Münster in July 2014 (Spekkers et al. 2017) reveals that important learnings could already have been made. According to the (former) head of the fire brigade of the city of Münster (pers. communication on 28 June 2022), an elderly gentleman with mobility impairments checked the basement for damage. While he was downstairs, a window broke and the inflowing water flooded the basement very fast. The man was trapped and drowned. In the second case, an elderly gentleman drove in a borrowed car to get some equipment for damage mitigation. Most probably he lost control of his vehicle and was later found drowned. Both incidents reflect very dominant fatal pathways and accident dynamics of July 2021 (see Figure 2). Hence, a better and continuous documentation of flood fatalities and structured lessons learned evaluations of severe events would reveal vulnerabilities earlier and could initiate interventions, e.g., tailored crisis and risk communication.

In August 2002, it was reported that several people died during or after evacuations (Reimer 2002; Jonkman and Kelman 2005). In 2021, the document analyses revealed that at least two elderly people died after being evacuated from their retirement homes in NRW. Since their death was considered “natural” (see Table 1 for an explanation), they were, however, not officially counted as flood-related fatalities. Since the number of similar cases could not be retrieved from the files reliably, they were neglected in this analysis, too, although it is acknowledged that the role of evacuations needs further investigation.

## 3.2 Influence of socio-demographic factors

IRDR (2015) recommends distinguishing reports on flood fatalities by their gender, age, and geographical sub-areas (such as municipalities) as a tertiary data level in loss databases. These three characteristics are assumed to reflect specific vulnerabilities or event characteristics. In fact, gender, age and health status are commonly considered important indicators of a person's vulnerability to flooding (e.g., Jonkman and Kelman 2005; Green et al. 2019; Petrucci 2022), with children and the elderly being considered particularly vulnerable to flooding, e.g., because their stability in flooded areas is worse than that of (healthy) adults (Jonkman and Penning-Rowsell 2008). Therefore, socio-demographic data of the 49 flood fatalities in NRW were analyzed in detail and it was tested whether there are significant differences between gender and age groups with regard to the circumstances and dynamics of the accidents. Figure 3 summarizes significant findings. The three geographic sub-areas will be introduced in section 3.3; the results for gender and age groups will be discussed in what follows. Further socio-demographic factors like the level of education, income or household size might also play a role for a person’s vulnerability, but could not be retrieved for all cases. However, the coding scheme could be expanded by these variables. Anecdotal evidence suggests that the social network and advise given by family members, neighbors or friends could play an important role for (not) performing certain behaviors. Still, this topic needs further research.

Of the total of 49 people investigated, 31 were male (63.3 %) and 18 female (36.7 %). The deviation from the total population of NRW (49.1 % male, 50.9 % female, as of 31 December 2020) is confirmed by a chi-square goodness-of-fit test (p-value: 0.0467). Hence, men died significantly more often in the flood of July 2021 than their share in the total population would suggest. This pattern is not unusual: in Europe, the USA and Australia, about 65 % of flood victims are male (Petrucci 2022). This is generally attributed to three factors: first, men more often have outdoor occupations; this fact applies to one man from NRW in July 2021. Secondly, men are significantly overrepresented in search and rescue operations. In July 2021, this applies to three firefighters who died during or after official rescue operations in NRW (see Figure 2), as well as another firefighter and a fifth man, who died during private rescue operations, while there's no such case among the females (note that a female firefighter died in Rhineland-Palatinate). These five men correspond to 16% of the 31 male victims. Third, it was found that men tend to behave riskier in flood situations (Badoux et al. 2016; Petrucci 2022). In fact, the chi-square tests only revealed significant differences between males and females with regard to their activities, i.e., their behavior during the flood ($p < 0.01$; see Figure 3). The analyzed documents further suggest that 4 out of 31 men (13 %) ignored warnings and safety instructions. Such evidence was not found for deceased women. Men also took more often care of checking equipment such as pumps in the basement or were checking, repairing or reducing damage (11 out of 31 men, i.e., 35 %, versus 3 out of 18 women, i.e., 18 %), which can be interpreted as risky behavior in case of a flash flood, but also as precautionary behavior with the aim to reduce damage. Women, on the other hand, were slightly more often caught by surprise by flood waves at home (4 out of 18 women, i.e., 22 %, versus 4 out of 31 men, i.e., 13 %) and outdoors, where they were more often on foot in flooded areas (7 out of 18 women, i.e., 39 %, versus 2 out of 31 men, i.e., 6 %). Accidents in or near a vehicle show almost an equal distribution between the genders (4 out of 18 women, i.e., 22 %, versus 5 out of 31 men, i.e., 16 %). Hence, the findings for NRW in general match the findings for gender difference in the literature (e.g., Petrucci 2022). However, the data reveal that risky and precautionary behavior cannot always be clearly distinguished. In case of fast onset floods, precautionary behavior to mitigate damage can be too risky.



| Significance of Chi-Squared tests (Likelihood-Quotient) | Gender | Age | Sub-Area |
|---|---|---|---|
| Medical cause of death | | | ** |
| Time of accident (day/night) | | * | *** |
| Victim's activity | ** | ** | ** |
| Accident location in flood hazard zone (HQ-extrem) | | | (*) |
| Dynamic of the accident | | ** | * |
| Location (detail) | | ** | * |

| Legend | |
|---|---|
| *** | p ≤ 0.001 |
| ** | p ≤ 0.01 |
| * | p ≤ 0.05 |
| (*) | p ≤ 0.1 |
| | p > 0.1 |

Figure 3: Summary of significant differences across gender, age groups and geographic subareas with regard to other variables of the fatal accidents in July 2021 in NRW (see legend for the level of significance p of the chi-square test).

With regard to age, the two youngest fatalities in NRW were 18 years old, the oldest 86. The median age of the 49 flood victims was 65 years (mean: 62.65 years). A comparison with the age distribution in the general public reveals that people over 60 years are clearly overrepresented among the fatalities, while the age groups of children and adults between 21 and 50 years are underrepresented (Table 2). Therefore, it was further explored what might explain the higher mortality among the elderly in July 2021. For this purpose, the data set was split into 17 people aged 60 years or younger and 32 people who were older than 60 years and tested for differences. Times and locations of the accidents, as well as the activities and accident dynamics between the ≤ 60-year-olds and over-60-year-olds revealed significant differences, but there were no significant differences in the medical causes of death (Figure 3).

With regard to activities, over-60s checked systems in the basements significantly more often or they tried to check, remove or reduce damage (Figure 4a). In total, this activity was fatal for 13 elderly people. The proportion of those who were flooded in their home by surprise is also slightly higher among the elderly (six people aged >60). For the younger people, on the other hand, rescue operations (private or fire brigade) played a more important role, and they were more often on foot in the affected area. The accident locations differed accordingly: only 24 % of the ≤ 60-year-olds died in a building, while this applies to 66 % of the over-60s. Similar patterns were reported in Petrucci's review (2022).

The analysis further reveals that accident dynamics are much more diverse among the elderly. Most frequently, they were trapped or entrapped in a flooded basement or ground floor flat. However, in basements other processes were also observed, especially falls and overstraining or overexertion (cf. Figure 4b and Figure 2).

Table 2: Distribution of flood fatalities in July 2021 by age group in comparison to the total population of North Rhine-Westphalia (NRW; as of 31 Dec. 2020).

| Age group | # Fatalities in July 2021 | Share | # General population of NRW as of 31 December 2020 | Share |
|---|---|---|---|---|
| 0 to 14 years (children) | 0 | 0.0 % | 2 510 010 | 14.0 % |
| 15 to 20 years | 3 | 6.1 % | 1 062 157 | 5.9 % |
| 21 to 30 years | 2 | 4.1 % | 2 196 917 | 12.3 % |
| 31 to 40 years | 1 | 2.0 % | 2 246 813 | 12.5 % |
| 41 to 50 years | 4 | 8.2 % | 2 176 060 | 12.1 % |
| 51 to 60 years | 7 | 14.3 % | 2 917 472 | 16.3 % |
| 61 to 70 years | 10 | 20.4 % | 2 198 654 | 12.3 % |
| 71 to 80 years | 15 | 30.6 % | 1 522 843 | 8.5 % |
| >80 years | 7 | 14.3 % | 1 094 644 | 6.1 % |
| Total | 49 | | 17 925 570 | |

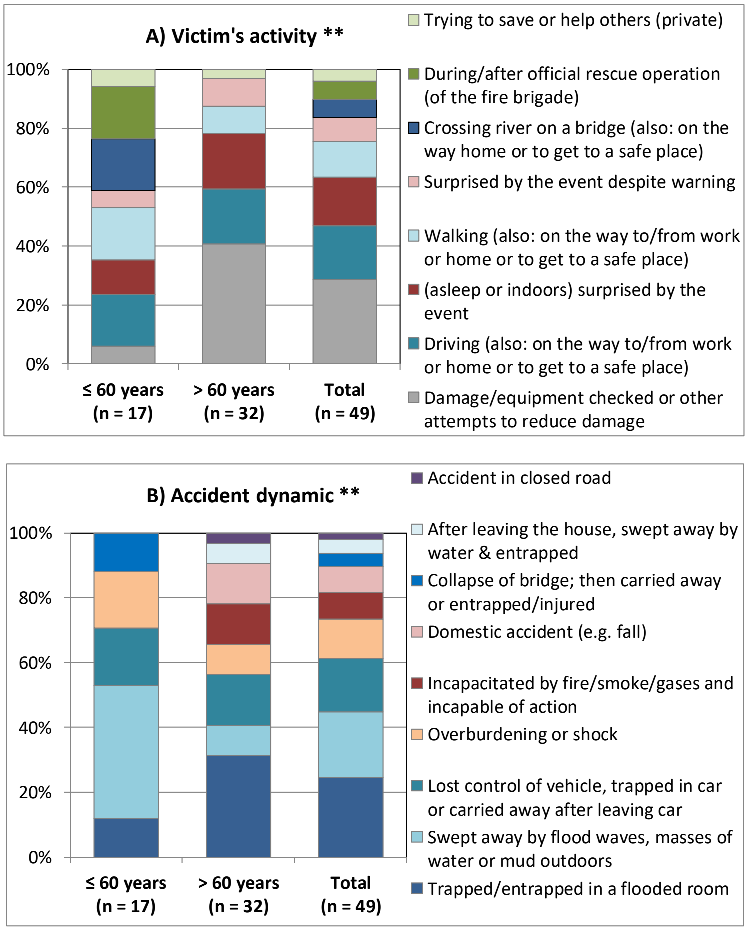


Figure 4: Activities of flood victims (A), and accident dynamics (B) among the 49 flood fatalities in NRW in July 2021 per age group (chi-square p-value ≤ 0.01: **; see also Figure 3).

It should be noted that for 25 people some pre-existing health conditions were mentioned in the documents analyzed, but only five of them were ≤ 60 years of age. Since there is hence a clear correlation between age and pre-existing conditions in the data, the influence of pre-existing conditions on the circumstances of death is not presented. In addition, it is worth noticing that the pre-existing conditions were not detected the main cause of death except for cases with an internal medical cause of death: heart conditions, high blood pressure or overweight were assumed to contribute to the death. However, among of the seven people who died due to internal medical causes, three were under 60 years of age, two of whom were rescue workers who collapsed during or after an official fire brigade operation. In the documents analyzed, other fire brigades also reported serious illnesses such as heart attacks or strokes among rescue workers after the end of their mission in July 2021. On the one hand, this illustrates the enormous strain on rescue workers during such an operation. On the other hand, this finding suggests that previously ill or older members of the fire brigades should take on less stressful tasks and take more breaks.

## 3.3 Spatial distribution of fatalities and influence of geographic factors

For an assessment which role the flood magnitude played, the geographical distribution of the accident locations was mapped on the municipal level. Figure 5 reveals a concentration of fatalities in the upper catchments of the rivers Rur and Erft. In the town of Schleiden (including the community of Gemünd), nine people died due to extreme flooding of the Olef, Urft and smaller water bodies in the upper catchment area of the river Rur. Three more people in Nettersheim, two in Kall and one in Hellersthal can also be attributed to this catchment area. The daily precipitation for 14/15 July 2021 proves that high precipitation amounts between 125 and 150 mm in 24 hours occurred in this area (Kron et al 2022). According to WVER (2021), a return period of 1000 years was exceeded in this area at three precipitation stations (Blankenheim, Dahlem-Schmidtheim and Kall-Sistig) for the rainfall totals from 13 to 15 July 2021. These villages and towns are all located upstream of the big Rur reservoir (retention capacity of >200 million m³), which was completely filled in July 2021 – even the spillway was activated – but still prevented severe flooding further downstream. Together with the catchment of the upper Ahr river, where one person died in the municipality of Blankenheim (NRW), these cases are grouped into the subsample G1 (n = 16).

Figure 5 reveals that most fatalities occurred in the overall catchment area of the river Erft with its tributary Swistbach – in the following referred to as subsample G2 (n = 20). In detail, five people died in Rheinbach, four in Swisttal, five in Bad Münstereifel, three in Euskirchen, two in Zülpich and one person near Erftstadt in a flood-related traffic accident.

High precipitation was also recorded in the headwater catchments of the rivers Erft and Swistbach (Kron et al. 2022). At the rainfall gauge Euskirchen-Steinbach, a rainfall total of 179 mm was measured on 14 July 2021; in the southern and south-eastern catchment area, more than 130 mm of precipitation was recorded over the entire area, so that a 100-year precipitation event was clearly exceeded across the region (Erftverband 2021). The water level of an extreme flood, on which the hazard maps are based, was exceeded at almost all gauging stations (Erftverband 2021).

For statistical reasons all other fatalities were summarized in the sub-sample G3 (n = 13). It thus includes two cases each from Geilenkirchen, Cologne and Leichlingen and one person each from Altena, Düsseldorf, Inden near Jülich, Kamen, Rösrath-Hoffnungsthal, Solingen and Werdohl (Figure 5). The sub-sample thus extends over a very large and naturally very heterogeneous area; precipitation amounts were also very different, as was the timing of the flood. While the flood peaked in the late evening or at night in the areas G1 and G2, the timing was more diverse in area G3.

Figure 5 also depicts flood warning gauges available in July 2021. Their availability varies greatly: in the comparatively small catchment area of the river Urft (G1) there are three flood gauges on the Urft and Olef, whereas the upper Erft river and the river Swistbach (G2) are each equipped with only one gauge (at Arloff and Morenhoven, respectively). Furthermore, there was no flood warning gauge upstream of the cities of Bad Muenstereifel or Rheinbach, which the inhabitants could refer to in a flood event, which considerably hampers their ability to be alerted and prepared for a flood. Sub-area G3 is too heterogeneous to allow a statement on this.

In the following, we examine whether and how accident locations, dynamics, etc. differ in the three sub-samples. In fact, the chi-square test (likelihood quotient) indicates significant differences in the sub-areas for all six variables investigated (Figure 3). However, due to the very small number of cases per sub-area, these values should not be over-interpreted. Figure 6 nevertheless illustrates that there seem to be area-specific phenomena.

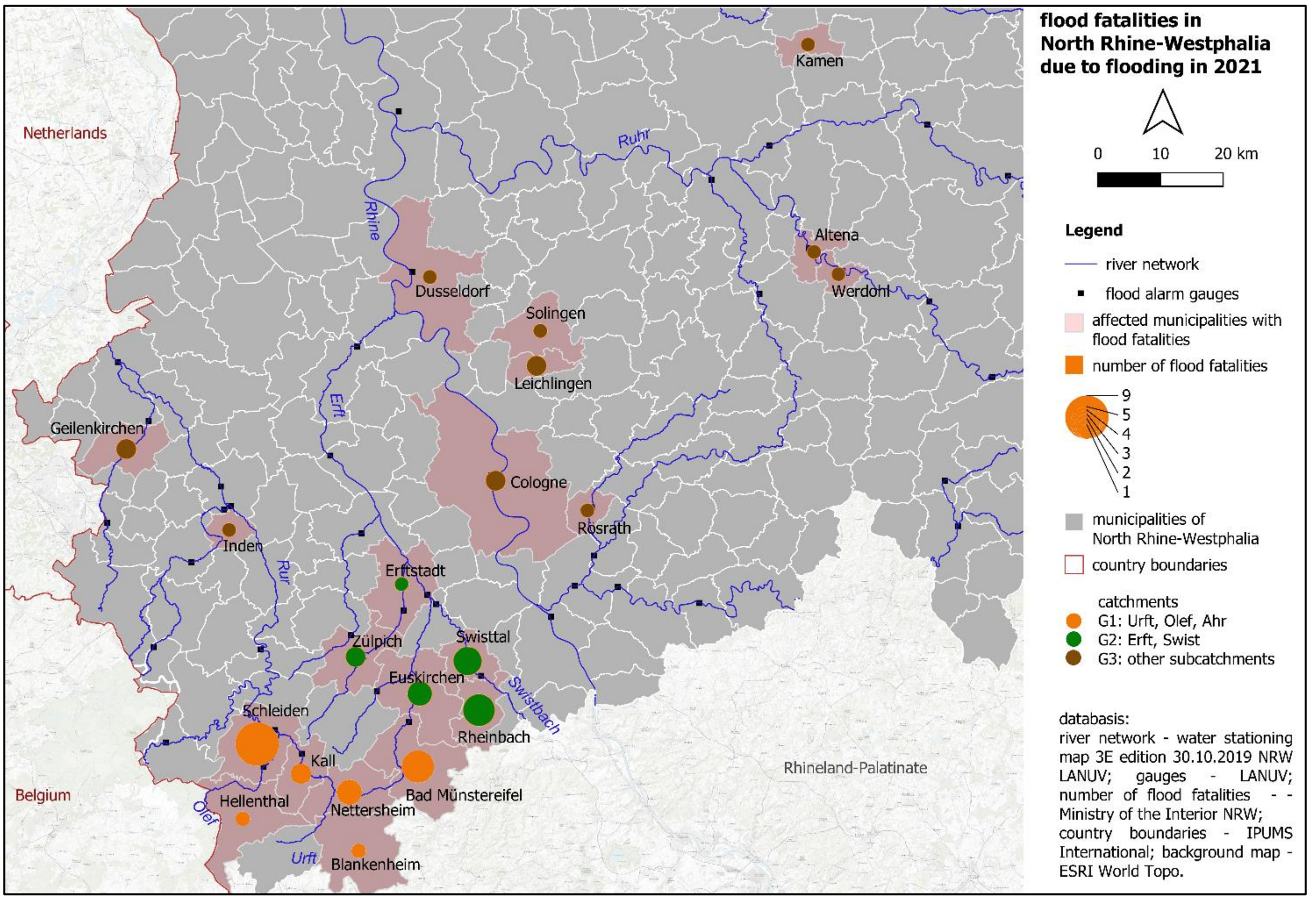


Figure 5: Geographical distribution of flood fatalities of July 2021 in North Rhine-Westphalia at the level of municipalities; note that only water bodies with flood warning gauges are shown in the map.

With regard to the medical causes of death, it is striking that the proportion of people who suffered death by drowning is significantly higher in areas G1 and G2 than in G3. In both areas (G1 and G2) there was only one person each with an internal medical cause of death. In addition to the 15 drownings in G2, one death was caused by suffocation and one by a combination of suffocation and drowning. Two people succumbed to their injuries (polytrauma). The picture is clearly different in area G3: Here, internal medical causes of death are the most frequent cause with five cases, followed by drowning in three cases and two cases each of suffocation and drowning as well as burns (and resulting injuries). In one case, death from suffocation was certified (Figure 6A). This means that in areas G1 and G2, physical/direct exposure to the floodwater played a significantly greater role than in area G3. For rescue operations and emergency response, darkness probably was an additional complicating factor (Figure 6B). Particularly, in area G1 and G2 the flood peaked at night, when other social interactions are limited, too, as is the recognition of flooded areas due to short visibility ranges outdoors.

The accident locations (Figure 6F) and activities (Figure 6C) also differ significantly across the regions: in sample G3, there are considerably more cases in which people checked a system in their basement or wanted to check, repair or reduce damage there. In addition, some people were surprised by the event (one despite warning), and two people died during rescue operations. Only three accidents happened outdoors, all others indoors (Figure 6F). This differs in the areas G1 and G2, where several people died outdoors while traveling by car or on foot. In area G1, the proportion of those who were surprised by the flood event indoors is also higher. In contrast to the other areas, this mostly happened in ground floor apartments (Figure 6F). In areas G1 and G2, the three accidents already mentioned also occurred when crossing bridges (one in G1, two in G2). These hazards were not specially highlighted in flood hazard maps, in some cases they do not even show flooding there. Overall, the hazard maps in area G1 perform worse than in G2 and G3, although the differences here are only slightly significant (Figure 6D). However, the poorer performance of the hazard maps in area G1 fits with the event magnitude and the fact that more people were flooded by surprise, while in area G3 more people controlled their property-level flood adaptation measures, namely pumps, or reduced damage (Figure 6C).

Though not clearly captured by the coding scheme, individual reports from sub-area G1 suggest that five people tried to leave their flooded properties horizontally, i.e., by driving (two people) or walking away (three people), and then were caught by the water outside. In contrast, just one case of a failed vertical self-evacuation attempt (coupled with an underestimation of the hazard in area G3) was described. In this case, a ladder or scaffolding was climbed, which was swept away by the water; later rescue attempts also failed. In contrast, there were at least six successful vertical self-evacuations in the vicinity of documented fatalities in areas G1 and G2, e.g., by holding out in the attic, in a tree (for several hours) or escaping the flooded zone via the roofs. Although some of these people also had to be rescued by the fire brigade or were treated in hospital, these attempts did not end fatally. In fact, a more systematic study of successful (self-)evacuations and rescues is proposed in the literature (e.g., by Petrucci 2022), but not implemented. A structured analysis of such success-stories is difficult to perform and tends to be anecdotal. In fact, one impressive incident was reported several times (including reports in newspapers) in July 2021: since water was entering a retirement home, employees tried to protect the building from the water masses with sandbags. During this work a tree fell and entrapped one of the employees. Since the water continued to rise, the situation became life-threatening, but a first responder held the employee's head above water, preventing her from drowning until the fire brigade arrived who freed the injured woman alive. This example illustrates a successful life-saving response in a dangerous situation and suggests that a systematic analysis of successful strategies could start with a closer look at flood-related injuries and rescue operations.

In consistency with Gruntfest et al. (1978), all the above-mentioned findings suggest that in case of doubt, a vertical escape is more promising than a horizontal one if the water has already flooded a residential area. This is especially relevant for steep catchments, where fast flowing water very quickly poses a serious risk to life. However, the sequence of events in July 2021 in the Ahr valley in Rhineland-Palatinate also shows the limits of this strategy: when buildings are heavily damaged by the water, collapse or are completely washed away, vertical escape routes inside buildings and on roofs no longer exist. In addition, a certain level of physical fitness is necessary, which cannot be assumed for older people or people with mobility impairments. This makes them particularly vulnerable (see section 3.2). Therefore, they should be particularly considered in risk communication and evacuation plans. In fact, in severely affected headwater catchment like the sub-areas G1 and G2 in NRW timely evacuation could have been a crucial safety measure. The concentration of flood fatalities in these headwater catchments calls for better plans for evacuation and traffic control with more systematic closures of (potentially) flooded roads. These measures, however, need proper forecasts and timely warning. This supports the request by Vinet et al. (2016) to improve the flood forecasting, warning and response system (FFWRS) in flash flood areas. Due to short reaction times of the catchments, the FFWRS relies more on precipitation forecasts and hydrological modelling than on water level monitoring at gauges. Therefore, ways how to deal with uncertain forecasts have to be developed and trained, too. Analyses by Brown and Graham (1988), who examined dam breaches, warning lead times and the number of fatalities in relation to exposed people, illustrate that around 90 minutes lead time are enough to prevent a substantial number of fatalities assuming that the warning triggers (self-)evacuation. A similar study was aimed at for the flood of 2021 in NRW, but did not deliver meaningful results. Still, in the survey on the warning situation in July 2021 provided by Thieken et al. (2023), responses from the subarea G2 (n = 576) resulted in a higher percentage of people who had not been warned, i.e., 42 % in comparison to 35 % in all of NRW (n = 892) and 20 % in area G3 (n = 259).

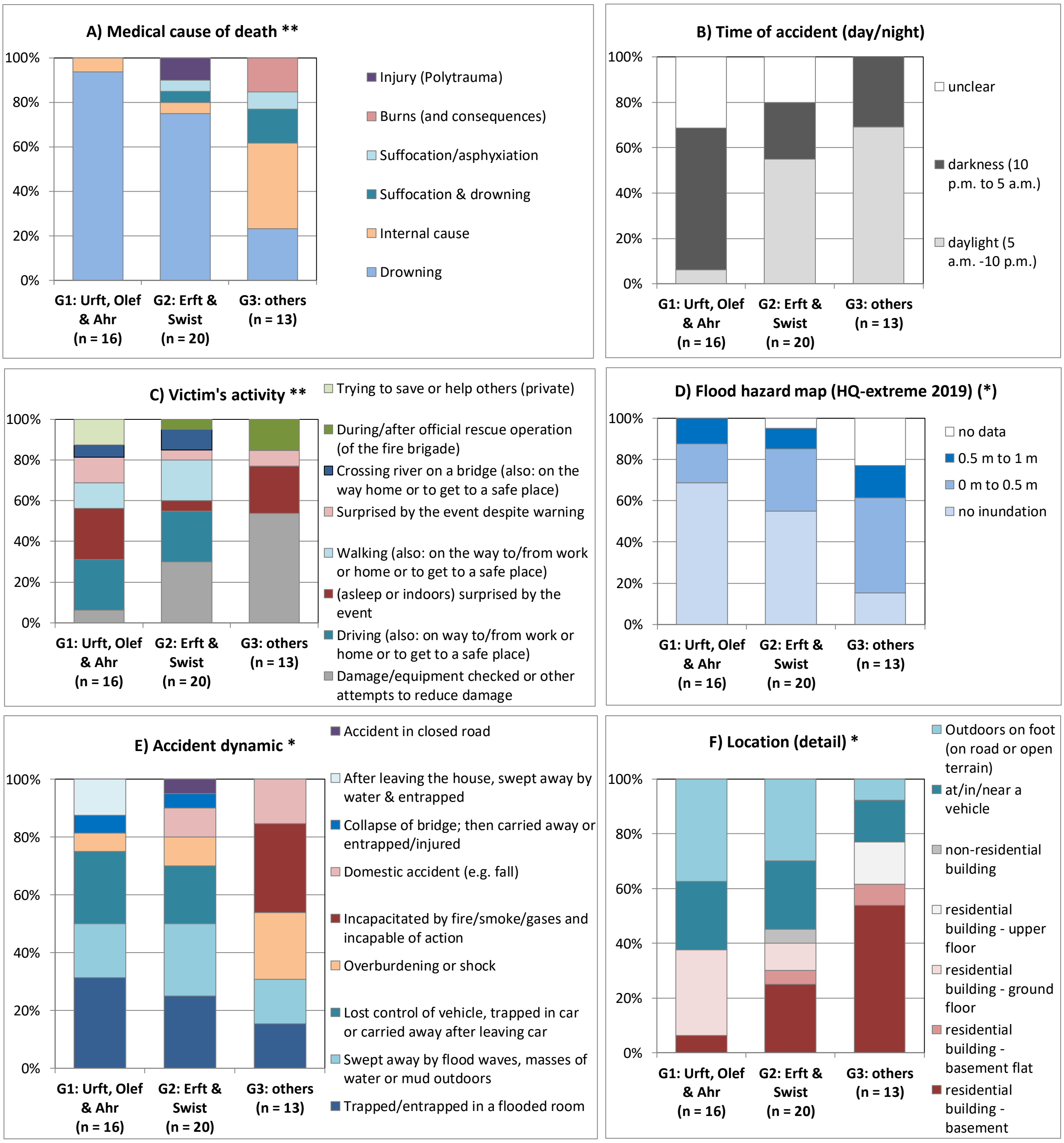


Figure 6: Medical causes of death (A), time of day of the accident (B), activities (C), accident dynamics (E) and localities (F), and representation of the accident location in the flood hazard maps (D) for an extreme flood (HQ-extreme, as of 2019) for the 49 flood fatalities in NRW in July 2021, differentiated by subarea (significance level of the chi-square test likelihood ratio: (*) ≤ 0.1; * ≤ 0.5; ** ≤ 0.01; *** ≤ 0.001; see also Figure 3).

# 4 Conclusions and recommendations

In this paper, the circumstances in which 49 people lost their lives in the floods of July 2021 in North Rhine-Westphalia (NRW) were examined in order to derive recommendations for an improved flood risk management. The study revealed significant differences between indoor and outdoor incidents, but also differences across gender and age groups, as well as sub-areas with different event magnitudes.

In fact, elderly people (>60 years) were particularly at risk; they account for two thirds of the dead. This calls particularly for a continuous and age-specific risk communication.

In recent years, risk communication in Germany focused very much on property-level adaptation to mitigate damage, which was introduced in the Federal Water Act in 2005. Our analyses reveal that many people died in their basements while attempting to inspect property-level adaptation measures or to inspect, reduce, or repair damage. To substantially decrease such cases in future, the Federal Water Act and/or the North Rhine-Westphalian State Water Act should be amended to clarify that the duty to take precautions and mitigate damage ends when there is a health risk – safety first! Furthermore, risk communication in flash flood areas should generally focus more on adequate behavior that reduces direct exposure to the floodwater and the risk of drowning. Potential life-threatening situations during fast onset-flooding and the priority to be safe have to be emphasized. In flood-prone areas with typical slowly-rising water levels and respective longer warning times, property-level adaptation to reduce damage can remain an important topic of risk communication, but should be accompanied by a greater focus on reducing risky behavior during damage mitigation. Particularly, risk awareness for domestic accidents and overexertion should be created among elderly people, while dangerous situations outdoors and in a (flooded) vehicle should be discussed with younger people at public schools and driving schools.

Flood hazard maps, which have been available nationwide since 2013 and are updated every six years, are an important element of risk communication. In July 2021, they indicated no risk from flooding at around half of the 49 accident locations illustrating the exceptional event magnitude and suggesting shortcoming of the maps. Hence, the underlying flood frequency statistics must certainly be updated. In addition, potential hazards at bridges due to clogging, backwater effects or collapses need to be re-evaluated and depicted in the maps. Concepts on how risks from surface runoff in hilly regions outside the water courses could be combined with flood hazard maps need to be developed. Here, event characteristics (especially flood magnitudes and times of occurrence), but also warnings and evacuations may play a role.

Since several people were surprised by water entry into their buildings or outdoors on their way home or when trying to leave the flooded zone, it is assumed that a lack of warning played a role in around one third of the cases. . While warnings remain challenging and uncertain in fast-responding catchments, improvements of the whole flood forecasting, warning and response system are certainly needed. Warnings remain ineffective if they are not translated into adequate action. In heavily affected areas, timely evacuation can be a life-saving measure. How to take such decisions under uncertain forecasts deserves particular attention in headwater catchments. Respective trainings and support of local civil protection should be developed. For the general public, warning levels and flood hazard maps should be better linked to identify hazard zones and to enable appropriate behavior including (self-)evacuation. This should be harmonized across Germany including a common definition of the scenario that determines the extreme flood hazard map.

Some fatal pathways could have been already detected in earlier events and lessons could have been learned if structured event documentations and impact data recordings were in place. In fact, this is requested by the Sendai Framework for Disaster Risk Reduction 2015-2030, whose implementation is challenged in Germany since civil protection as well as water management are responsibilities of the states (*Länder*). Hence, joint efforts are needed to establish documentation procedures and achieve consistent data. Among other things, this includes a reassessment and harmonization of definitions of flood fatalities, especially with respect to indirect immediate cases, such as deaths after evacuations. The coding scheme presented in this paper could serve as a template for future events. In fact, the findings of this study could have been achieved with considerably less effort if a more structured documentation had been prepared beforehand and carried out during the event

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# Author contributions (CRediT)

AT: Conceptualization, Data curation, Methodology Formal Analysis, Supervision, Visualization, Writing – original draft, Writing – review & editing. MLZ: Formal Analysis, Visualization, Writing – review & editing. PB: Methodology, Formal Analysis, Writing – review & editing.

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