



Jonas Laudan | Viktor Rözer | Tobias Sieg | Kristin Vogel
Annegret H. Thieken

Damage assessment in Braunsbach 2016

data collection and analysis for an improved understanding of
damaging processes during flash floods

Suggested citation referring to the original publication:
Natural Hazards and Earth System Sciences 17 (2017), pp. 2163–2179
DOI <https://doi.org/10.5194/nhess-17-2163-2017>
ISSN (print) 1561-8633
ISSN (online) 1684-9981

Postprint archived at the Institutional Repository of the Potsdam University in:
Postprints der Universität Potsdam
Mathematisch-Naturwissenschaftliche Reihe ; 653
ISSN 1866-8372
<https://nbn-resolving.org/urn:nbn:de:kobv:517-opus4-418392>
DOI <https://doi.org/10.25932/publishup-41839>



Damage assessment in Braunsbach 2016: data collection and analysis for an improved understanding of damaging processes during flash floods

Jonas Laudan¹, Viktor Rözer², Tobias Sieg^{1,2}, Kristin Vogel¹, and Annegret H. Thieken¹

¹University of Potsdam, Institute of Earth and Environmental Science, Karl-Liebknecht-Strasse 24–25, 14476 Potsdam, Germany

²GFZ German Research Centre for Geosciences, Department of Hydrology, Telegrafenberg, 14473 Potsdam, Germany

Correspondence to: Jonas Laudan (jlaudan@uni-potsdam.de)

Received: 6 December 2016 – Discussion started: 15 December 2016

Revised: 26 October 2017 – Accepted: 31 October 2017 – Published: 6 December 2017

Abstract. Flash floods are caused by intense rainfall events and represent an insufficiently understood phenomenon in Germany. As a result of higher precipitation intensities, flash floods might occur more frequently in future. In combination with changing land use patterns and urbanisation, damage mitigation, insurance and risk management in flash-flood-prone regions are becoming increasingly important. However, a better understanding of damage caused by flash floods requires ex post collection of relevant but yet sparsely available information for research. At the end of May 2016, very high and concentrated rainfall intensities led to severe flash floods in several southern German municipalities. The small town of Braunsbach stood as a prime example of the devastating potential of such events. Eight to ten days after the flash flood event, damage assessment and data collection were conducted in Braunsbach by investigating all affected buildings and their surroundings. To record and store the data on site, the open-source software bundle KoBoCollect was used as an efficient and easy way to gather information. Since the damage driving factors of flash floods are expected to differ from those of riverine flooding, a post-hoc data analysis was performed, aiming to identify the influence of flood processes and building attributes on damage grades, which reflect the extent of structural damage. Data analyses include the application of random forest, a random general linear model and multinomial logistic regression as well as the construction of a local impact map to reveal influences on the damage grades. Further, a Spearman's Rho correlation matrix was calculated. The results reveal that the damage driving factors of flash floods differ from those of river-

ine floods to a certain extent. The exposition of a building in flow direction shows an especially strong correlation with the damage grade and has a high predictive power within the constructed damage models. Additionally, the results suggest that building materials as well as various building aspects, such as the existence of a shop window and the surroundings, might have an effect on the resulting damage. To verify and confirm the outcomes as well as to support future mitigation strategies, risk management and planning, more comprehensive and systematic data collection is necessary.

1 Introduction

Flooding is a common hazard in central Europe, resulting in high economic losses (Munich Re, 2017). To promote and tailor local planning, flood risk management policies such as the European Floods Directive (2007/60/EC) set up framework conditions for member states to implement flood risk management on national, regional and local levels. Risk assessments and policy decisions are expected to take different flood types into account (e.g. coastal floods, riverine floods, pluvial floods, flash floods), according to the local circumstances (BMUB, 2007). In Germany, for instance, storm surge and river flooding are dominant and were therefore considered risks with national significance. Due to recent severe riverine flooding in eastern and southern parts of Germany, particularly in August 2002 and June 2013, the flood risk management system and the relevant legislation have

been substantially improved by the Omnibus Flood Protection Act of 2005 and the EU Floods Directive (2007/60/EC) and its implementation in the Federal Water Act of 2009 (e.g. Thieken et al., 2016b). In support, a large body of literature exists that addresses the topic of riverine flooding in Germany and its effects as well as demands on people, policy makers and general planning. In this regard, risk assessment strategies and effects of preparedness decisions are presented and extensively discussed with a strong focus on recent major riverine flood events. (e.g. Bubeck et al., 2013; Kienzler et al., 2015; Bracken et al., 2016; Osberghaus and Philippi, 2016; Thieken et al., 2016b; Kundzewicz et al., 2017). However, when implementing the EU Floods Directive in Germany, surface water flooding and flash floods were not considered significant risks and were thus neglected. This assessment is currently questioned due to destructive flash flood events in May and June 2016 that caused damages of EUR 2.6 billion (Munich Re, 2017).

Flash floods are defined as rapid flood events as a result of very intense, timely and concentrated precipitation, which is potentially enhanced by orographic features (Gaume et al., 2009; Borga et al., 2014). According to Gaume et al. (2009), flash floods can be triggered by diverse hydrological and meteorological processes and are, compared to riverine and pluvial flooding, associated with a higher number of fatalities. Whereas pluvial floods are related to urban areas and caused by sewage overflow and surface run-off (Maksimović et al., 2009), flash floods usually occur in mountainous regions, where they can trigger debris flows and/or hyperconcentrated flows. Debris flows and hyperconcentrated flows are characterised by the amount of transported and suspended sediment. With a sediment concentration between 60 and 80 volume percent, the quantity of solid material is often higher for debris flows than for hyperconcentrated flows (Gaume et al., 2009). Both flow types show a variation in grain size distribution and deposition characteristics as well: while debris flows potentially carry large debris, boulders and gravel, hyperconcentrated flows transport finer sediments (Pierson and Costa, 1987; Gaume et al., 2009; Totschnig et al., 2011; Hungr et al., 2013; Borga et al., 2014).

Weather extremes in Europe are expected to occur more frequently, leading to strong storms, droughts and heavy precipitation in various regions (Beniston et al., 2007; Murawski et al., 2015; Volosciuk et al., 2016). More intense and concentrated rainfall in central Europe might increase the hazard of severe flash flood events, not only in mountainous regions but uplands as well, affecting regions which were previously not perceived as flood prone. Further, an increased risk due to a change in exposed objects and their vulnerability can be detected, which is mainly influenced by urbanisation and economic growth as well as changing land use patterns (Thieken et al., 2016a; European Environment Agency, 2017). As a result, flash floods are progressively perceived as a serious hazard in central Europe. Yet, the implications on elements

at risk are poorly understood and assessing their vulnerability, also in comparison to riverine floods, is challenging.

Vulnerability can be defined as the tendency for elements at risk to suffer negative effects and damage if affected by a specific hazard (Cardona et al., 2012). Regarding flash floods, vulnerability and risk estimations were already conducted in several studies. For instance, Papathoma-Köhle (2016) pointed out that vulnerability assessments for flash floods or debris flows need to be reviewed and adjusted constantly. In her study, an indicator-based method was used for assessing the vulnerability of elements at risk which are exposed to debris flows in South Tyrol. In this regard, the relevance of building characteristics and location for vulnerability estimations were highlighted. Similarly, Fuchs et al. (2012) conducted a study which describes the vulnerability of elements at risk, based on clusters of similar damage ratios caused by flood events. This spatial approach revealed that higher damage ratios are not only a result of stronger floods, debris flows or hyperconcentrated flows, but are also dependent on land-use patterns and the characteristics of the elements at risk, such as the type and year of construction. With regard to non-alpine environments, Hlavčová et al. (2016) performed a post-hoc analysis of three strong flash flood events which occurred between 1988 and 2004 in northern Slovakia, focusing on the hydrology as well as hydraulic and topographic properties of the catchment areas. They showed that the modelling of flash flood events is accompanied by major uncertainties due to the lack of data and overall non-linear relationship between precipitation, run-off and catchment properties.

Concerning flash floods in central Europe and particularly non-alpine environments, we are in the early stages of understanding specific and subsequent damaging processes from such floods. Especially in respect to vulnerability estimations of the elements at risk as well as the damage driving factors, flash floods are insufficiently understood. Yet, it can be assumed that damage processes of flash floods differ from those of riverine floods, highlighting the need for elaborate research in this field. Riverine floods commonly emerge on the basis of large catchment areas after long-lasting rainfall or snowmelt, which leads to high surface and groundwater run-off and relatively slow-rising water levels. In contrast to riverine floods, flash floods originate from catchments in which geographical features such as steep slopes and defined channels result in rougher flow dynamics in terms of velocity, sediment transport and discharge (Borga et al., 2014). Here, potential damage to buildings comprises erosion and physical impacts, which, on the other hand, do not seem to be distinct damage patterns in riverine flooding (see Kreibich et al., 2009).

To obtain a better understanding of the damage processes of flash floods as well as of effective mitigation options, a comprehensive damage database that links process dynamics and intensities with damage and loss is needed, but is currently not available. Consequently, we present the flash flood

in Braunsbach, a town in the district of Schwäbisch Hall in Baden-Württemberg, Germany, as a case study, having collected and analysed data in order to add to the knowledge of damage caused by flash floods and governing factors.

Intense rainfall at the end of May and beginning of June 2016 over central Europe led to severe surface water flooding and flash floods, which were partly accompanied by mud and debris. Several municipalities mainly in the south of Germany were hit, eleven people lost their lives and infrastructure and buildings were heavily damaged (GDV, 2016). The insured losses of these events amounted to EUR 1.2 billion (GDV, 2016) and the overall loss was estimated at EUR 2.6 billion (Munich Re, 2017), an extraordinary monetary loss caused by flash floods in Germany. The district of Schwäbisch Hall in Baden-Württemberg was particularly affected. Moreover, at the beginning of June 2016 the municipality of Rottal-Inn in southern Bavaria was hit by flash flooding, triggered by the same weather conditions (GDV, 2016).

A small village in Schwäbisch Hall named Braunsbach faced an especially severe flash flood on 29 May that caused high damage to buildings and infrastructure. The village of Braunsbach contains just about 1000 residents, yet due to the devastating character and abruptness of this event, the media attention was high and policymakers were interested. The monetary losses for the municipality of Braunsbach (~ 2500 residents) were estimated at EUR 104 million, which is more than 90 % of the estimated EUR 112 million of total damage in Schwäbisch Hall (Landkreis Schwäbisch Hall, 2016). The catchment of the creek primarily responsible for the inundation in May 2016, the Orlacher Bach, is only about 6 km² in size and characterised by steep slopes, in which the stream descends ~ 180 m over a distance of 3.1 km. Heavy rainfalls in the catchment area between 18:45 and 20:00 of 29 May resulted in an estimated accumulated precipitation of 60 mm, based on radar data which was recorded 70 km south of Braunsbach. Due to inconsistencies and attenuation effects, the data were corrected up to 153 mm after the approach of Jacobi and Heistermann (2016), (see Bronstert et al., 2017). The extraordinary rainfall patterns finally led to the severe flash flood, which was accompanied by massive amounts of debris and rubble. Streets along the main run-off channel were blocked by layers of debris, up to a thickness of 2 to 3 m, while numerous houses in the area showed severe structural damage. Given the town size, event duration and catchment area, the losses were extremely high. Eventually, this event and similar cases of severe flash flooding in Germany triggered a reassessment of local risk and revealed that the processes and impacts of flash floods are insufficiently understood (in Germany), also showing that research on and management of this particular flood type needs to catch up, particularly in comparison to river floods.

Our research paper follows two major objectives. Using the flash flood in Braunsbach as a case study, it is aimed at identifying, analysing, comparing and discussing factors

that govern damage caused by this event, applying different linear and non-linear methods. As a second issue, the digital methods used for the ex post damage data collection in Braunsbach and the creation of this database are presented and discussed to demonstrate accompanying challenges as well as successes during the field work.

2 Methods





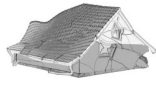
Collecting and analysing data on structural and non-structural damage to buildings is valuable for understanding specific damage processes, helping to design and assess effective mitigation measures and creating damage models which can be used to estimate potential monetary losses *ex ante*. Thus, a digital survey was designed to collect relevant information in Braunsbach which can be used for detailed post-hoc analysis. The type of recorded information is based on existing literature on flood damage surveys (e.g. Thielen et al., 2005; Schwarz and Maiwald, 2007; Merz et al., 2010; Molinari et al., 2014).

2.1 Contents of the survey

The survey as well as the data collection was implemented with KoBoCollect, a self-explaining and network-based open-source software which was developed by the Harvard Humanitarian Initiative together with the Brigham and Women's Hospital in 2014 (KoBoToolbox, 2016). The software is designed for quick and reliable information collection after natural disasters or in humanitarian crises. Open-source software, as a method for data collection and gaining knowledge, is increasingly becoming important within the field of natural hazards (Eckle et al., 2016; Klonner et al., 2016). For instance, OpenStreetMap (OSM) and other voluntary geographic information services help to create comprehensive databases of up-to-date geospatial data which also can be used for natural risk assessment (Schelhorn et al., 2014; Vaz and Arsanjani, 2015; Yang et al., 2016).

The gathered information in Braunsbach included an estimation of damage grades of the affected buildings ranging from D1 (no structural damage, slight non-structural damage) to D5 (very heavy structural damage, very heavy non-structural damage). For this classification, the scheme developed by Schwarz and Maiwald (2007) was adopted to obtain a consistent database and to ensure comparability with follow-up studies and with data on riverine flood damage (Table 1). Since monetary losses could not be recorded shortly after the event, this classification scheme further offers options for potential subsequent loss estimations. Additionally recorded information included the GPS coordinates, the address (for internal computational use only), the inundation depth at the building in centimetres, visible damage caused by debris, visible contamination by oil or sewage, the building material and type, specific precautionary measures at the

Table 1. Assignment of damage grades D_i to damage cases: examples from the flood in August 2002 (after Schwarz and Maiwald, 2007).

Damage grade	Damage pattern (sketch)
D1: no structural damage, slight non-structural damage – moisture penetration of walls and ceilings	
D2: no structural damage to slight structural damage, moderate non-structural damage – moisture penetration and contamination – small cracks in walls, dented doors and windows	
D3: moderate structural damage, heavy non-structural damage – larger cracks in walls, dented doors and windows – beginning subsidence of the building – replacement of building components necessary	
D4: heavy structural damage, very heavy non-structural damage – collapse of load-bearing walls, large cracks – replacement of load-bearing components necessary	
D5: very heavy structural damage, very heavy non-structural damage – collapse of large building parts – demolition necessary	

building, the building usage (residential, commercial, public, etc.), the number of storeys and types of outbuildings, the estimated year of construction, the perceived condition of the building before the event, existing shop windows on the ground floor, the existence of a cellar, the sealing degree of the near surroundings and the exposition (of the building) in flow direction. All variables except for the address, inundation depth, storeys and the estimated year of construction were pre-coded with the option to record open answers or NA values, resulting in a nominal-, ordinal- and interval-scaled data structure. The complete survey with variable descriptions can be seen in Table 2. A more detailed description of the data set, as well as the anonymised data, can be found in Vogel et al. (2017a).

2.2 On-site data collection

The on-site damage assessment was carried out between 7 and 8 June 2016, i.e. 9 to 10 days after the event. The digital survey was conducted by a team of five researchers who investigated all buildings in Braunsbach affected by the flash flood using mobile tablet computers with an integrated GPS function.

Some of the flooding characteristics, such as flow velocities and grain size as well as the degree of erosion and amount of suspended material, could not reliably be determined in the aftermath of the event. Hence, the exposition

of the building was used as a proxy instead. It is assumed that the degree of exposition can be related to flow velocities, hydrostatical forces and (to a certain extent) to sediment/debris load, which in turn leads to different erosion rates at the buildings' foundation. The exposition in flow direction describes the exposition of building walls, corners or parts to the direction and area of the main run-off channel. In this case, a high exposition means that at least one side of the building was fully exposed to water and potential debris flows. A medium exposition was assumed when parts of the building were exposed. Sheltered buildings are characterised by a low exposition.

A thermographic camera (model Testo 876, 160×120 pixels) was used to validate and to derive the inundation depth in such cases, where a reliable estimation through visible traces and marks was not possible. This was done by detecting the remaining moisture in the walls – caused by inundation – through slight differences in surface temperature. A second advantage of the thermographic camera was the detection of different building materials, which may be covered externally (i.e. plastered half-timbered houses could still be identified as such; see Vogel et al., 2017b).

Table 2. Features of 94 buildings affected by flooding in Braunsbach, Germany, recorded between 7 and 8 June 2016, and their frequency of occurrence.

Variable	Characteristics	No.
Damage grade	D1 (no structural damage, slight non-structural damage)	39
	D2 (no to slight structural damage, moderate non-structural damage)	34
	D3 (moderate structural damage, heavy non-structural damage)	5
	D4 (heavy structural damage, very heavy non-structural damage)	6
	D5 (very heavy structural damage, very heavy non-structural damage)	5
	No damage	5
	NA	0
Inundation depth (cm)	Integer value	88
	NA	6
House type	Single-family house	46
	Apartment building	25
	Semi-detached house	3
	Terraced house	0
	NA	20
Building material	Masonry	71
	Half-timbered	26
	Wood	10
	Concrete	0
	Steel	0
	Rubber	0
	NA	1
Building usage	Residential	58
	Commercial	8
	Combined/mixed	21
	Public services	6
	NA	1
Near surrounding sealed	Yes	64
	Mainly yes (small areas around not sealed)	21
	Mainly no (larger areas around not sealed)	8
	No	0
	NA	1
Exposition in flow direction	High (at least one side of the building fully exposed to water flow)	34
	Medium (parts of the building exposed to water flow)	34
	Low (sheltered by other buildings/slightly exposed to water flow)	26
	NA	0
Damage caused by debris	Yes	55
	No	37
	NA	2
Building condition before event	Good	45
	Medium	46
	Bad	1
	NA	2
Outbuildings present	Yes	32
	No	59
	NA	3

Table 2. Continued.

Variable	Characteristics	No.
Type of outbuilding	Garage	11
	Carport	1
	Barn	8
	Shed	7
	Summerhouse	1
	Greenhouse	0
	Conservatory	0
	Other	7
Number of storeys	Integer value	93
	NA	1
Shop window	Yes	18
	No	74
	NA	2
Having cellar	Yes	30
	No	57
	NA	7
Estimated construction year	Integer value	88
	NA	6
Structural precaution	Higher ground floor	19
	Different (building) materials (of cellar and ground floor)	24
	Protection of cellar duct	3
	Other	4
	No precaution	49
	NA	3
Contamination visible	Yes	77
	No	15
	NA	2
Contamination type	Oil	4
	Chemicals	0
	Sewage	0
	Mud	77
	Other	0

NA means not available.

2.3 Post-hoc data analysis

The data were preprocessed and analysed/prepared in R 3.3.1 and QGIS 2.14.3, using the R packages randomForest, randomGLM and nnet. Since our study aims to identify and analyse damage driving factors of flash floods, the following variables and binary-coded variable expressions were considered and used as predictor variables for the damage grades:

- Building material (binary-coded):
 - masonry (selected also in case of unidentifiable building material)
 - wood
 - half timbered.
- Precaution (binary-coded):
 - different (building) materials (of cellar and ground floor)
 - higher ground floor
 - no structural precaution visible.
- External forces:
 - inundation depth
 - exposition in flow direction
 - contamination visible (binary-coded).
- Resistance parameters:
 - (building) condition before event

- estimated construction year.
- Various:
 - shop window present (binary-coded)
 - near surrounding sealed
 - having cellar (binary-coded)
 - outbuilding present (binary-coded)
 - private building usage (binary-coded).

The choice of the variables which were specifically analysed was based on both judgements (e.g. if the near surrounding is sealed or if an outbuilding or shop window is present) and the existing literature. Here, Thieken et al. (2005), Merz et al. (2010) and Maiwald and Schwarz (2015) give an overview of important damage-influencing factors in cases of (river) flooding, including building characteristics, precaution measures and contamination.

2.3.1 Models and correlation tests

Detecting non-linear and non-monotonic relationships within recorded data becomes increasingly important with regard to flood loss modelling and associated uncertainties (Kreibich et al., 2016). Consequently, a random forest model (RF) (Breiman, 2001) was chosen as a method of analysis due to its potential to display non-linear relationships between variables. The random generalized linear model (RGLM) (Song et al., 2013) was constructed as an alternative model to compare the results of the non-linear RF to a method which implies linear variable coherences. Both models use the same predictor variables and the damage grade as dependent variables (excluding cases where no damage was recorded) in order to identify potential damage driving factors (Figs. 1 and 2).

The RF is calculated with 500 trees and 4 random variables per split. The number of trees represents the default settings of the algorithm. The number of variables per split corresponds to the square root of the total variable count (16 in this case, resulting in 4 random variables per split). The RGLM takes 100 iterations with 50 samples per iteration (bag) and a varying count of variables (2 to 16) per bag. Also, the number of iterations within the RGLM represents the default settings. The number of samples per bag was set to two-thirds of the total number of observations in the data set (73 in this case due to the need to complete observations, resulting in 50 observations selected by bootstrapping). The count of variables per bag is randomly chosen between 2 and the total count of variables. The variable/feature importance of the RF is given by the mean decrease Gini, which describes the loss in model performance when permuting the feature values (Breiman, 2001). A higher mean decrease Gini indicates higher importance of the particular variable for the RF model prediction. The feature importance of the RGLM is expressed through the selection count of a variable for the model prediction.

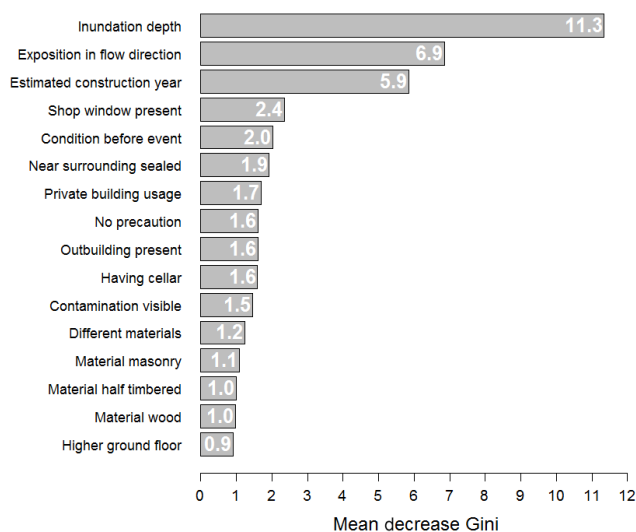


Figure 1. Random forest feature importance (mean decrease Gini) for the response variable damage grade.

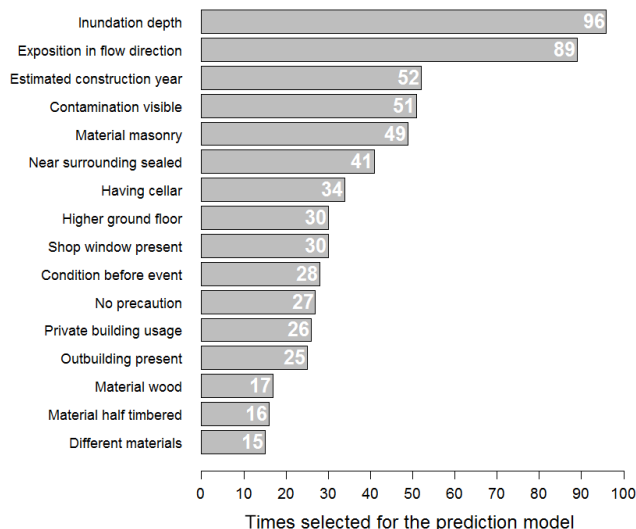


Figure 2. Random generalized linear model feature importance (times selected) for the response variable damage grade.

By using feature-forward selection, a higher selection count of a particular variable indicates a stronger predictive power within the RGLM model (Song et al., 2013). The performance of both models is given by the rate of false classifications, based on the out of bag predictions. The relative number of cases which were not recognised as the true class is hereby shown in percent (see Sect. 3.2).

Categories with a nominal variable structure (i.e. building usage, building material and structural precaution measures) exist in a binary format, allowing for basic correlation tests. Thus, the identified feature importance from the models was compared to the results from a Spearman’s rank correlation matrix. The Spearman’s rank correlation was chosen due to

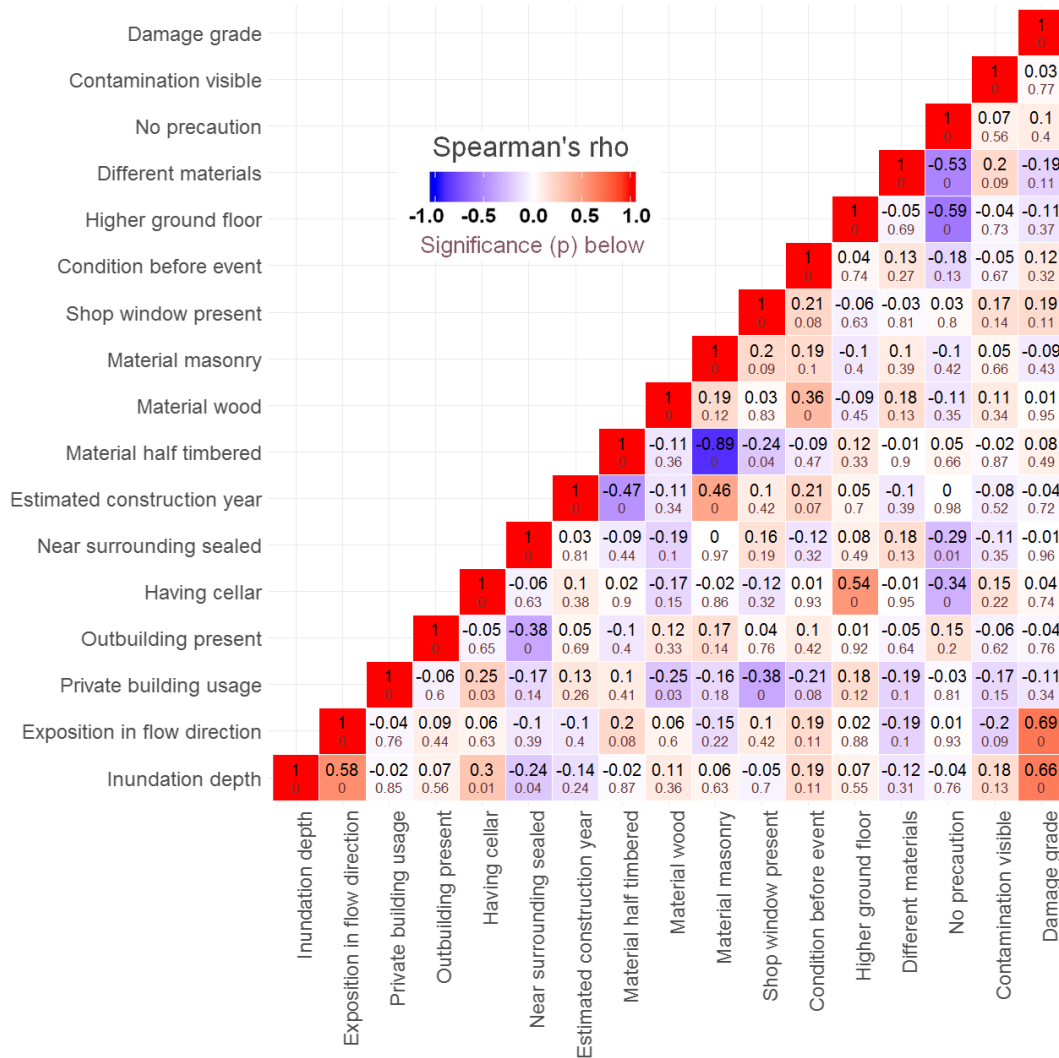


Figure 3. Spearman’s rank correlation matrix and correlation significance of relevant variables (see Table 2 for a description of the variables). The count of complete cases for the analysis was 73.

its advantage of being suitable to analyse variables with different scales of measurements and indicates the strength of monotonic relationships. Here, the same variables as in the RF and RGLM models were used (Fig. 3). An exhaustive list of variable correlations is attached in Appendix A, which is based on 51 complete observations within the data set.

Furthermore, a multinomial logistic regression was applied to test variable coherences between the damage grades and a local impact indicator (Fig. 4) which describes a combination of inundation depth and the buildings’ exposition in flow direction (the construction of the local impact indicator is explained in Sect. 2.3.2). By treating the damage grade as a categorical variable, the multinomial logistic regression model gives probabilities of category affinity, given a specific local impact. In order to obtain more data points per category and to reduce modelling uncertainties, the damage grades 3, 4 and 5 were combined into a single class (com-

pare Table 1). The inherent calculations are based on artificial neural networks (Ripley, 1996; Venables and Ripley, 2002) which again do not require any model-specific assumptions such as linearity.

2.3.2 Derivation of a local impact indicator

Maiwald and Schwarz (2015) give an up-to-date overview of factors which influence structural damage to buildings in cases of flooding. The building material, condition (before the event) and age are especially important factors that are related to a building’s resistance potential. Factors such as inundation level, flow velocity, fluid density, specific energy and contamination relate to “action” parameters and describe external forces (Maiwald and Schwarz, 2015; Milanesi et al., 2015). Thus, in our study, the inundation depth measured at the building and the building’s exposition in flow direction

were combined to create a local impact value, which can be seen as a proxy for local flood-related impact and hydrostatic forces at the building. Consequently, we chose a combination of these factors where both contribute to equal extents. While the inundation depth has continuous values which are roughly uniformly distributed between 2 and 360 cm for 88 recorded observations (see Table 2), the exposition in flow direction is recorded in three classes (low, medium, high; see Table 2). To achieve comparable variable ranges, the exposition classes low, medium and high are transformed into the mean values of the lower (29 observations), middle (30 observations) and upper third (29 observations) of recorded water levels. The derived values 56, 135 and 232 fit into the range of observed water levels, enabling a combination of both attributes (Fig. 5). The calculated local impact corresponds to the sum of water level and transformed exposition value. Please note that the exposition values are not used to replace water levels but are only transformed into a comparable range.

Furthermore, a local impact map was created in QGIS (Fig. 6) by calculating Voronoi diagrams for the geocoded data points and solely displaying the area with affected houses. For simpler visual appearance and better distinction of the displayed data, the Voronoi diagrams were smoothed with a Gaussian filter. The local impact map is used for visualisation and comparison of the local impact indicator to the spatial distribution of the damage grades, since potential areas of similar local impact between and around the buildings are shown. However, it has to be noted that the local impact was measured directly at the buildings and is therefore hypothetical for the surrounding areas.

3 Results and discussion

The flash flood in Braunsbach was accompanied by a considerable amount of sediment and building rubble, potentially showing flow characteristics of debris flows such as those defined by Totschnig et al. (2011), Hungr et al. (2013) and Borga et al. (2014). Yet, a clear distinction between flash floods and debris flows is not always straightforward and could not be reliably determined in the field. Throughout our discussion, we will therefore use the term “flash flood” only. The following section begins with a general reflection on the data collection process, limitations and data quality. Thereafter, the damage-influencing factors are identified and discussed by applying different linear and non-linear methods. Finally, features such as the local impact and the damage grades are spatially visualised, helping to discuss our outcomes and illustrating the flash flood processes in Braunsbach.

3.1 Data collection and field work; assumptions and limitations

The in-field work load can be estimated at roughly 10 h, in which a team of five researchers was able to survey 96 buildings in Braunsbach (corrected to 94 observations after database checks), each specifying 18 variables. In addition, a picture has been taken along with the coordinates, the address and, if needed, further details regarding the building's usage. Table 2 provides an overview of the data types and frequency distributions. One week after the event, the structural damage to buildings and building characteristics were still assessable, since the main work within this period was focused on clearing the roads and establishing paths for large construction machinery as well as removing and cleaning the interior of affected buildings. The progress of the clean-up work was even beneficial for the damage assessment to a certain degree, as a thick layer of debris and rubble previously covered big parts of the damaged buildings. However, a few buildings could not be reliably examined, since debris and rubble were still considerably hampering the access.

When handling the thermographic camera it has to be pointed out that, even 1 week after the event, remaining moisture and visible traces could still be detected without problems. Yet, ascending humidity in the walls is a point to consider when using a thermographic camera for water level estimations. Rising moisture can distort the observation of actual water levels at the building. For that reason the thermal images were checked against estimations based on visible mud contamination and marks caused by water and transported debris as well. Since the thermally derived water levels matched well with visible traces, the inundation depth for buildings derived from thermal images could be accepted without any correction. Still, when using a thermographic camera for water level estimations on buildings, it has to be considered that the type of flood (flash flood, riverine flood) has an effect on the duration of the inundation and thus on the distinctness of visible moisture boundaries. Considering the short inundation times in Braunsbach, the overall good visibility of moisture boundaries was remarkable.

Overall, the in-field data collection was greatly facilitated by the use of KoBoCollect in terms of speed, handling of the gathered data and efficiency of data processing and analysis. However, to create a uniform database and to maintain consistency among the different team members throughout the data collection process, objective criteria for items such as the structural damage had to be defined. Therefore, careful preparations and agreements were carried out prior to the field trip off site as well as on site. In retrospect, we consider the data to be consistent because the team members had very similar opinions, e.g. on the damage grades or exposition in flow direction. Thus, a bias in the data set due to personal variations in expert judgement is expected to be low. This assumption is further supported by the engineering analysis of Maiwald and Schwarz (2016), who applied the same dam-

age classification system to assess the buildings structural damage in Braunsbach. Their report reveals that the distribution of the recorded damage grades after a second inspection (D1: 40, D2: 43, D3: 5, D4: 7, D5: 3) is relatively similar to the distribution presented in this study (D1: 39, D2: 34, D3: 5, D4: 6, D5: 5 as shown in Table 2). Although it is not known which damage grade was assigned to which building, it is likely that, even among people with different qualifications (experienced engineer, researcher or student), comparable results can be achieved and data collection can be consistent. This offers interesting options for crowd-sourced information collection using open-source software such as KoBoCollect, which can be helpful for scientific research.

3.2 Models and correlation tests

First, the collected data were used to identify damage driving factors by creating a random forest model (RF) and a random generalized linear model (RGLM) with the damage grade as response variable. In a next step, a Spearman's rank correlation matrix was constructed. In the following, the different model and correlation results are discussed and compared to each other.

The post-hoc data analysis revealed that the RF and RGLM both show a relatively poor model performance, based on the false classifications. Here, the percentages of false classifications for the RF are 33.3 % for damage grade D1, 41.9 % for D2 and 100 % for D3 and higher. The RGLM performed slightly better with a false classification of 33.3 % for D1 and 41.9 % for D2, 20 % for D3, 80 % for D4 and 100 % for D5. However, trends and relations of predictor variables with the damage grade can be derived. Both models give the highest feature importance for the damage grade to the inundation depth and the exposition (of the building) in flow direction. Here, the mean decrease Gini for the RF were 11.3 and 6.9 (average: 2.7), whereas the RGLM feature selection counts in 100 iterations were 96 and 89, respectively (average: 39) (Figs. 1 and 2). It is further shown that the RGLM compared to the RF indicates a different variable importance hierarchy for variables other than the inundation depth, the exposition in flow direction and the estimated construction year. This is due to different internal calculations of the variable importance, as explained in Sect. 2.3.1. Yet, this issue also suggests that, apart from the inundation depth, the exposition in flow direction and possibly the estimated construction year, differences in variable importance are less distinct in both models and the predictive power is low, which hampers the interpretation of the importance hierarchy when comparing both models.

Regarding the correlation tests, the highest positive (and significant) correlations can be seen between the damage class and the exposition of the building in flow direction as well as the damage class and inundation depth with values of 0.69 and 0.66, respectively (Fig. 3). Hence the correlation analysis strongly confirms the results of the RF and RGLM.

The detected a strong link of the exposition of the building in flow direction and the inundation depth to the caused damage makes sense, given the nature of the event and the mass of debris, water and mud flowing down the main channels within the village of Braunsbach. These results are confirmed by Maiwald and Schwarz (2016) as well, who identified the exposition of a building to the flow direction as an important parameter for potential structural damage. A high exposition in flow direction can be related to a higher flow force of water, higher flow velocities and intensities acting on a building. Investigations on these parameters regarding riverine floods by Kreibich et al. (2009) resulted in weak correlations with recorded damage grades of residential buildings. It is revealed that the exposition in flow direction is an especially significant damage driving factor of flash floods which does not show strong importance in riverine flooding.

The estimated construction year of a building displays a certain importance within the RF as well as the RGLM model with a mean decrease Gini of 5.9 and a feature selection count of 52 (see Figs. 1 and 2). In this case, the correlation analysis does not reveal any significant monotonic relationships between the estimated construction year and the damage grade (Fig. 3). Additionally, the building condition before the event displays only slight importance within the RF and a slight, non-significant correlation with the damage grade. Since the construction year is related to the overall preservation and the building's state of the art in terms of technology, it can still be assumed that newer buildings or buildings in a better condition have a higher resistance to structural damage. This is in line with Maiwald and Schwarz (2015), who consider the building age and condition to have an influence on the expected structural damage.

Further, a positive correlation, but of low significance, can be observed between the damage grade and the existence of a shop window with a value of 0.19 and a p value of 0.11 (Fig. 3). Accordingly, the RF model shows a certain variable importance with a mean decrease Gini of 2.4 (Fig. 1). Here, it can be assumed that a trend towards higher damage grades caused by shop windows on ground level which – if they break – create debris and water paths into the building. Also Maiwald and Schwarz (2016) underline the fact that broken windows may allow water and debris to accumulate inside the building, causing damage to sustaining building structures. Yet, our results might also be affected by the fact that, in this case study, buildings with shop windows mainly occur along the main street and city centre and are therefore located inside the main flow channels.

No (obvious) precaution at the property level indicates a slightly higher chance of higher damage by displaying a positive correlation of 0.1 with the damage class, although the significance is low (p value 0.4) and there is no remarkable importance within the RF and the RGLM models. Yet, this is in line with the negative correlation between the damage class and the precaution measure “different (building) materials (of cellar and ground floor)” of -0.19 which in fact

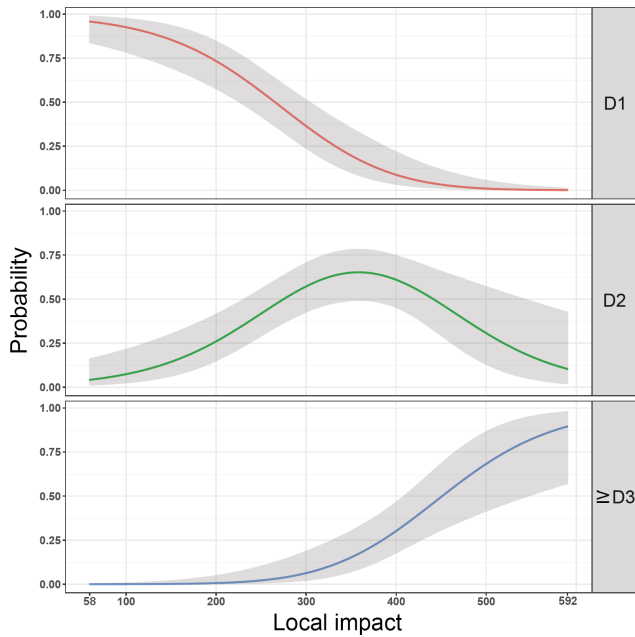


Figure 4. Probabilities of the damage grade predicted by the multinomial logistic regression model (see Table 2 and Sect. 2.3.2 for details on the damage grades and the local impact indicator). It can be seen how the probability for a specific group affinity changes with an increasing local impact value and shifts towards higher damage grades.

shows a low significance (p value 0.11) but still allows for meaningful assumptions. This is supported by Thieken et al. (2005) and Merz et al. (2010), who claim that different precautionary measures significantly reduce the damage to buildings in the case of flooding. Still, the question arises as to what degree precautionary measures, which were effective at riverine flooding, are suitable for mitigating structural damage to buildings in cases of flash flooding.

The building material masonry seems to have a slight damage-reducing effect by displaying a negative correlation of -0.09 (p value 0.43) with the damage class, while the half-timbered building material shows a very slight but non-significant positive correlation of 0.08 (p value 0.49) with damage. Interestingly, the RGLM model only considers the building material masonry as relatively important for the damage grade prediction, whereas the RF does not display a significant feature importance for all building materials. Although it is not clearly shown which distinct building material is related to lower structural damage, it can be assumed that if being hit by debris, half-timbered houses are more susceptible to structural damage than houses made of masonry and concrete due to their lower structural stability (Schwarz and Maiwald, 2007).

Overall, when performing detailed analyses such as models and correlation tests it has to be considered that the database of 94 data points is rather small and assumingly

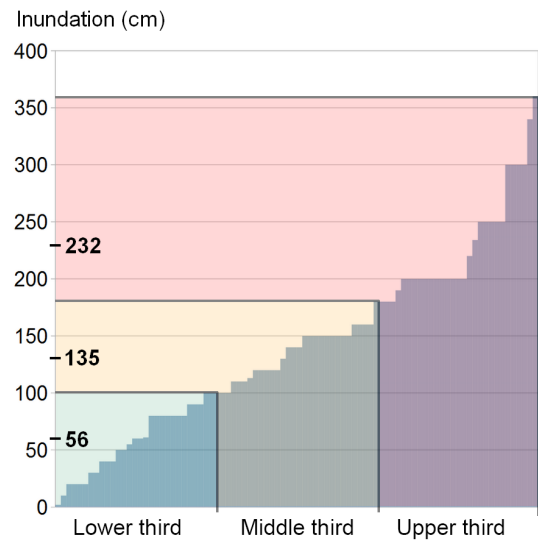


Figure 5. Deriving the local impact indicator. The recorded inundation depth is sorted in ascending order. By sorting, the relatively uniform distribution of the inundation values is shown, which allows for the general procedure. On the left, the mean values of the lower, middle, and upper third of the sorted inundation depth (56, 135, 232 cm) are given, which were used to replace the exposition classes, low, medium and high. This step enables a comparable variable range and the derivation of an interval-scaled indicator for further analysis.

insufficient for creating representative and universal results. This fact could also explain the low model performance and low significance in some of the cases discussed above. Nonetheless, it is important to point out the strong correlations in many cases of up to 0.69 (damage class and exposition in flow direction) revealing obvious damage driving factors and showing as well that the data collection within the team of different researchers was consistent.

3.3 Evaluation of the local impact

In Fig. 6, the town of Braunsbach as well as the corresponding local impact during the event and recorded damage grades are illustrated. The map reveals that highly damaged buildings and a strong local impact – which relates to hydrostatical and impact forces at the building (see Sect. 2.3.2) – occurred along the main run-off channels of water and debris during the event. Higher damage grades were also recorded in the lower-lying town regions, where the tributaries Or-lacher Bach and Schlossbach flow into the river Kocher, since debris and water accumulated in these areas and caused severe structural damage. Most of the higher damage grades are located in high local impact areas. Yet, especially in those areas, the degree of damage differs strongly, highlighting the complexity of damage driving processes that cannot be explained by the local impact alone. The flow characteristics of debris and rubble during severe flash floods can be un-

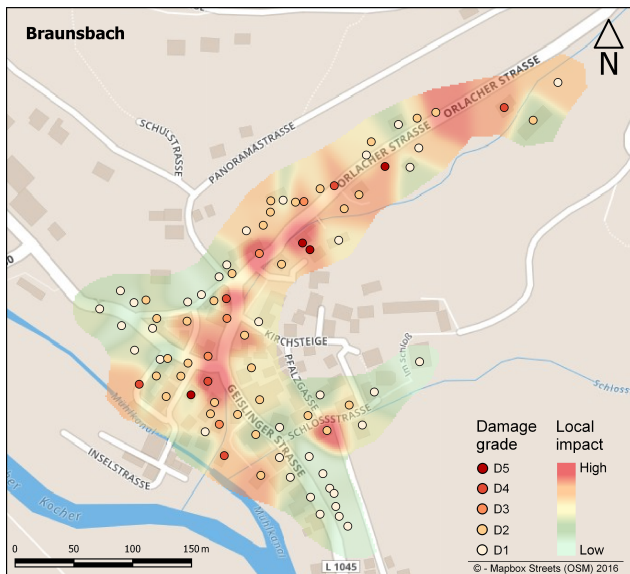


Figure 6. Map of the study area with the local impact, which is a combination of the inundation depth at the building and its exposition in flow direction (see text for further details). Further, the damage grades as recorded on site using the classification scheme of Schwarz and Maiwald (2007) are shown; see Table 1 for a verbal description of the damage grades.

foreseen and influenced by chaotic factors, changing sediment deposition as well as bedload processes (Totschnig et al., 2011; Hungr et al., 2013). Thus, it can be assumed that, during the flash flood in Braunsbach, chaotic factors and deposition of debris led to various damage patterns which remain inexplicable through quantitative analysis and modelling. This is strongly supported by the engineering report of Maiwald and Schwarz (2016), who claim that chaotic flow processes at the building caused by rubble and debris can greatly influence the inundation depth.

However, it is revealed that buildings with a high exposition in flow direction are more susceptible to severe structural damage, since the probability of large debris colliding with building walls is much higher and erosion of the foundation is more likely to happen. Also Maiwald and Schwarz (2016) stated that the recorded damage patterns differ from damage patterns caused by riverine flooding and appear to be more severe due to higher hydrodynamic stress and collision of debris with the building. Conversely, some buildings can benefit from shadowing effects of neighbouring buildings, which retain debris and suspended material to a certain degree.

To further evaluate the local impact indicator, a multinomial logistic regression was applied. By analysing the dependency between only the local impact indicator and the damage grade, the influence of external forces on the damage grade can be observed separately, since resistance parameters and building characteristics are neglected. As can

be seen in Fig. 4, there is a clear coherence of an increasing local impact and an increasing probability to belong to higher damage grades. However, in accordance with Fig. 6, Fig. 4 reveals again that external forces are not enough to explain the complex damage pattern. Especially for moderate impact values (around 300 to 400), non-negligible probabilities are assigned to all damage grades. Further, if higher local impact values are considered, a large model uncertainty has to be taken into account, which is shown by the 95 % confidence interval that covers a probability range of 45 % for the corresponding damage grade affinity. This means that i.e. given a local impact value of 550, the chance of belonging to class D2 ranges from 5 to 50 % and for greater equal D3 from 50 to 95 %. The large variability can be explained by the small number of observed data points with high local impact values. Additionally an increasing complexity of the damaging process for higher local impact values might contribute to the model uncertainty. Still, Fig. 4 shows that a local impact indicator can be suitable to evaluate the hydrostatical forces of this type of hazard, which, in addition to the characteristics of the element at risk, might allow vulnerability estimations such as performed by Papatoma-Köhle (2016).

It can be summarised that, next to individual flow and deposition processes of the flood, local factors, shadowing processes, and building characteristics shared a certain importance as damage driving factors in Braunsbach, highlighting the complexity of this event. This is supported by the findings of Fuchs et al. (2012), who revealed as well that damage to buildings is not only caused by flood-inherent processes and intensities, but is also influenced by building characteristics and is dependent on the general land use pattern.

According to Varnes (1984), risk reflects the expected damage which is governed by the hazard, exposure and vulnerability. Our results show that the local impact – which stands as a proxy for elements of the hazard processes and the exposure – is a meaningful external indicator of structural damage caused by flash floods, although it does not fully explain the recorded damage grades. It can be used either in multivariable damage models or in future risk maps for flash-flood-prone regions, introducing a valuable parameter for current and future risk and damage assessments. However, questions arise on how to collect necessary data for a reliable calculation of respective values. A feasible option is the derivation of values from aerial images in combination with digital elevation models to identify buildings which are exposed or shielded. Given the specific type of hazard, in this case flash floods, the local impact according to potential inundation depths and a building's exposition in flow direction could be estimated either manually or by algorithms. Prerequisites and challenges, however, comprise the accessibility of data, up-to-dateness, adequate image resolutions and quality checks. Here, further research is needed to evaluate potential uses of indicators such as the local impact, which can be relatively easily derived and hold a proxy character.

An alternative and quantitative approach to assessing hydraulic forces on buildings is the computation of flow fields during flash floods, taking into account local slope and fluid densities. This approach is presented by Milanese et al. (2015), who introduce a conceptual model which describes the acting forces on humans during rapid floods. However, detailed information about the building shape and geometry, friction coefficients as well as flow dynamics are required for the computation.

Consequently, when performing damage and risk assessments for flash floods in future, compromises must be found on issues such as the robustness and uncertainties of models, data availability and efficient data handling.

4 Conclusion

The evaluation and data analysis in this study resulted in important information about the impacts (damage to buildings) of the flash flood event in Braunsbach. It is revealed that not only does the water depth seem to be a risk factor in flash-flood-prone regions, often considered as the only damage driving factor in riverine flood loss modelling, but so does the exposition of a building in flow direction and susceptible building parts like shop windows. This result considerably differs from investigations on damage caused by riverine floods. Yet, the damage driving as well as damage reducing factors of flash floods are complex, often unpredictable, contingent upon the surrounding and dependent on certain building characteristics.

Knowing processes of flash floods and their impacts can help to create awareness for future events and support strategic planning with regard to similar emergencies. Concerning the European Floods Directive 2007/60/EC and its implementation in Germany, implications according to the German Federal Water Act exist. The evaluation of flash floods and surface water flooding as a significant risk would result in the obligation to create new nationwide hazard and risk maps. As a further consequence, the German Federal Water Act intends to place a building ban in all areas that are affected by a 100-year flood event, which would lead to serious consequences for local planning in flash-flood-prone regions. Therefore, flash floods are currently judged as a general risk throughout Germany.

Still, maps such as the presented local impact map could be a supportive and feasible first step in order to update and perform risk and damage assessments. The estimation of the local impact could be used in integrated risk management and strategic planning of mitigation measures against future hazards in Braunsbach or similar villages in that region. Thus, the introduced concept may be beneficial for the identification of potentially vulnerable locations on a small scale and within case studies, helping us to understand the potential future development of flash-flood-prone regions. However, further investigations are needed in order to verify the results and to obtain larger databases.

To facilitate data collection in the future, the case further demonstrates the potential of mobile devices and open-source applications. In the field, the simplicity, speed, quality and handling of information using the open-source application KoBoCollect particularly stood out as a great success. Even in a short time and with a small team of researchers it was possible to gather a fair amount of useful information that could be further processed and analysed. The public availability of the software makes it a fast and ad-hoc tool for assessing different kind of questions, usable in various research fields, not only for scientific but also for private uses. However, further aspects to discuss are whether the quality of crowd-sourced information is suitable for scientific investigations and how to approach and deal with possible limitations, security and copyright issues as well as uncertainties. Still, it can be concluded that open-source data collection software for mobile use has great potential as a scientific tool with which to generate extensive valuable data under challenging conditions. It should be especially considered in time-critical research applications such as ex post disaster analyses, as was demonstrated by the presented case of Braunsbach.

Data availability. The data sets used in this article are available at <https://doi.org/10.5880/figeo.2017.015> (Vogel et al., 2017a).

Appendix A

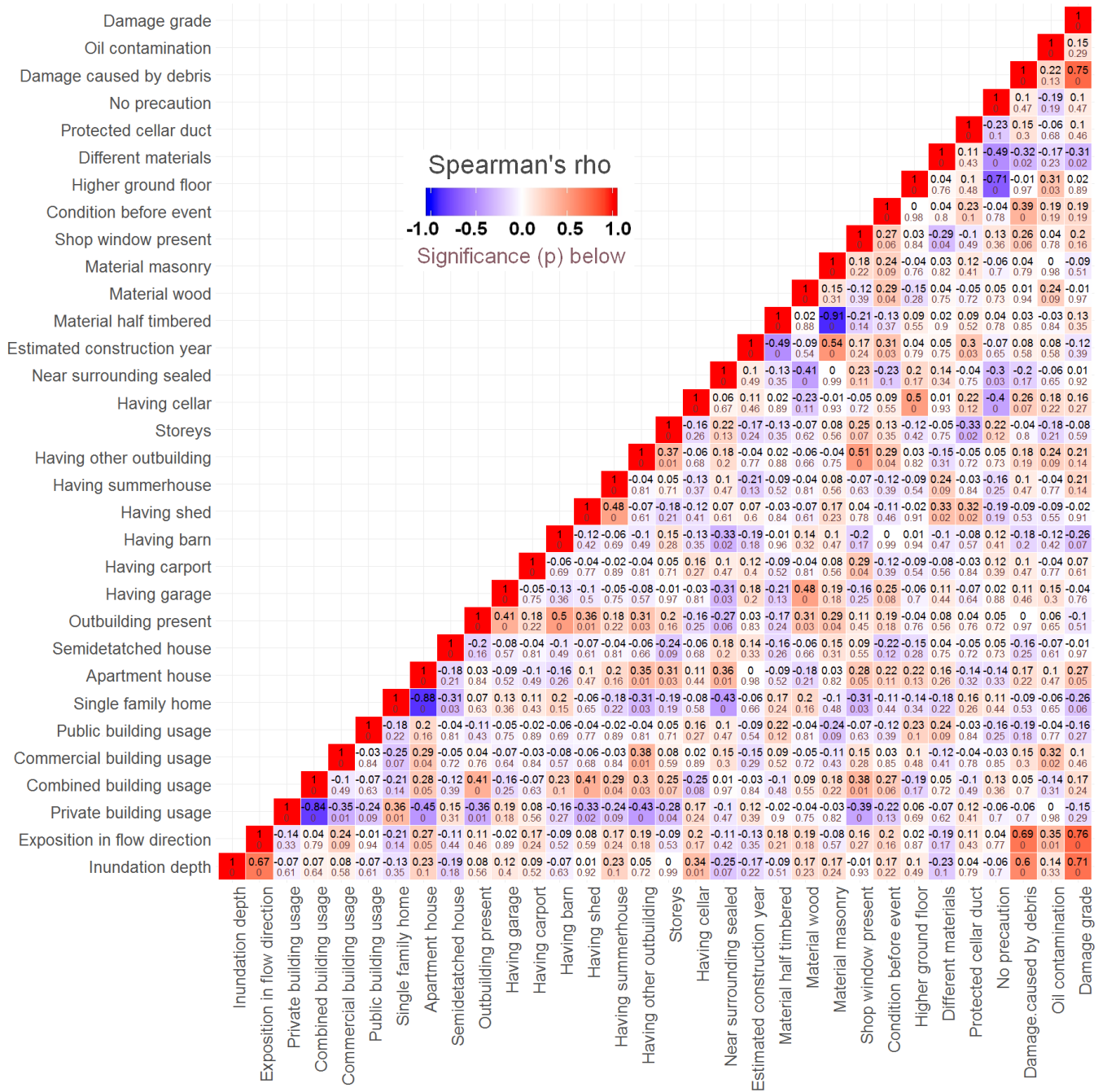


Figure A1. Spearman's rank correlation matrix and correlation significance of all variables in the data set. The count of complete cases for the analysis was 51.

Competing interests. The authors declare that they have no conflict of interest.

Special issue statement. This article is part of the special issue “Damage of natural hazards: assessment and mitigation”. It is not associated with a conference.

Acknowledgements. The presented work was developed within the framework of the Research Training Group “Natural Hazards and Risks in a Changing World” (NatRiskChange) funded by the Deutsche Forschungsgemeinschaft (DFG; GRK 2043/1). We further appreciate the help of Benjamin Winter, working at the alpS GmbH in Innsbruck, Austria, as well as giving thanks to Melanie Eckle, Benjamin Herfort, Carolin Klonner and Chiao-Ling Kuo from the University of Heidelberg for supporting the damage assessment in Braunsbach and providing additional mobile tablets for the data acquisition. Special thanks to the contribution of Viktor Rözer, who was partly funded by the German Ministry of Education and Research (BMBF, 03G0846B) via the project “EVUS – Real-Time Prediction of Pluvial Floods and Induced Water Contamination in Urban Areas”.

Edited by: Daniela Molinari

Reviewed by: three anonymous referees

References

- Beniston, M., Stephenson, D. B., Christensen, O. B., Ferro, C. A. T., Frei, C., Goyette, S., Halsnaes, K., Holt, T., Jylhä, K., Koffi, B., Palutikof, J., Schöll, R., Semmler, T., and Woth, K.: Future extreme events in European climate: an exploration of regional climate model projections, *Clim. Change*, 81, Suppl. 1, 71–95, <https://doi.org/10.1007/s10584-006-9226-z>, 2007.
- Borga, M., Stoffel, M., Marchi, L., Marra, F., and Jakob, M.: Hydrogeomorphic response to extreme rainfall in headwater systems: Flash floods and debris flows, *J. Hydrol.*, 518, 194–205, 2014.
- Bracken, L. J., Oughton, E. A., Donaldson, A., Cook, B., Forrester, J., Spray, C., Cinderby, S., Passmore, D., and Bisset, N.: Flood risk management, an approach to managing cross-border hazards, *Nat. Hazards*, 82, Suppl. 2, 217–240, <https://doi.org/10.1007/s11069-016-2284-2>, 2016.
- Breiman, L.: Random forests, *Machine learning*, 45, 5–32, <https://doi.org/10.1023/A:1010933404324>, 2001.
- Bronstert, A., Agarwal, A., Boessenkool, B., Fischer, M., Heistermann, M., Köhn, L., Moran, T., and Wendi, D.: Die Sturzflut von Braunsbach am 29. Mai 2016: Entstehung, Ablauf und Schäden eines “Jahrhundertereignisses”. Teil I: Meteorologische und Hydrologische Analysen, *Hydrologie und Wasserbewirtschaftung*, 61, 150–162, https://doi.org/10.5675/HyWa_2017,3_1, 2017 (in German).
- Bubeck, P., Botzen, W. J. W., Kreibich, H., and Aerts, J. C. J. H.: Detailed insights into the influence of flood-coping appraisals on mitigation behaviour, *Global Environ. Change*, 23, 1327–1338, <https://doi.org/10.1016/j.gloenvcha.2013.05.009>, 2013.
- Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB): Directive 2007/60/EC of the European Parliament and of the Council – of 23 October 2007 – on the assessment and management of flood risks, *Official Journal of the European Union*, L, 27–34, 2007.
- Cardona, O. D., van Aalst, M. K., Birkmann, J., Fordham, M., McGregor, G., Perez, R., Pulwarty, R. S., Schipper, E. L. F., and Sinh, B. T.: Determinants of risk: exposure and vulnerability, in: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, edited by: Field, C. B., Barros, V., Stocker, T. F., Qin, D., Dokken, D. J., Ebi, K. L., Mastrandrea, M. D., Mach, K. J., Plattner, G.-K., Allen, S. K., Tignor, M., and Midgley, P. M., A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, UK, and New York, NY, USA, 65–108, 2012.
- Eckle, M., De Albuquerque, J. P., Herfort, B., and Zipf, A.: Leveraging OpenStreetMap to support flood risk management in municipalities: A prototype decision support system, *ISCRAM 2016 Conference Paper*, Rio de Janeiro, Brazil, May 2016.
- European Environment Agency: Climate change, impacts and vulnerability in Europe 2016 – An indicator-based report, 1, Luxembourg, <https://doi.org/10.2800/534806>, 2017.
- Fuchs, S., Orntsmüller, C., and Totschnig, R.: Spatial scan statistics in vulnerability assessment: an application to mountain hazards, *Nat. Hazards*, 64, 2129–2151, <https://doi.org/10.1007/s11069-011-0081-5>, 2012.
- Gaume, E., Bain, V., Bernardara, P., Newinger, O., Barbuc, M., Bateman, A., Blaškovičová, L., Blöschl, G., Borga, M., Dumitrescu, A., Daliakopoulos, I., Garcia, J., Irmescu, A., Kohnova, S., Koutroulis, A., Marchi, L., Matreata, S., Medina, V., Preciso, E., Sempere-Torres, D., Stancalie, G., Szolgay, J., Tsanis, I., Velasco, D., and Viglione, A.: A compilation of data on European flash floods, *J. Hydrol.*, 367, 70–78, 2009.
- GDV – Gesamtverband der Deutschen Versicherungswirtschaft: Naturgefahrenreport 2016, Berlin, 2016 (in German).
- Hlavčová, K., Kohnová, S., Borga, M., Horvát, O., Štastný, P., Pekárová, P., Majerčáková, O., and Danáčová, Z.: Post-event analysis and flash flood hydrology in Slovakia, *J. Hydrol. Hydromech.*, 64, 304–315, <https://doi.org/10.1515/johh-2016-0041>, 2016.
- Hungr, O., Leroueil, S., and Picarelli, L.: The Varnes classification of landslide types, an update, *Landslides*, 11, 167–194, <https://doi.org/10.1007/s10346-013-0436-y>, 2013.
- Jacobi, S. and Heistermann, M.: Benchmarking attenuation correction procedures for six years of single-polarized C-band weather radar observations in South-West Germany, *Geomatics, Nat. Hazards Risk*, 7, 1785–1799, <https://doi.org/10.1080/19475705.2016.1155080>, 2016.
- Kienzler, S., Falter, D., Jentsch, S., and Thieken, A. H.: Reduktion von Hochwasserschäden im Zusammenspiel von staatlicher und privater Vorsorge – eine Fallstudie an der Mulde, *KW Korrespondenz Wasserwirtschaft*, 8, 680–687, <https://doi.org/10.3243/kwe2015.11.002>, 2015 (in German).
- Klonner, C., Marx, S., Usón, T., De Albuquerque, J. P., and Höfle, B.: Volunteered Geographic Information in Natural Hazard Analysis: A Systematic Literature Review of Current Approaches with a Focus on Preparedness and Mitigation, *ISPRS Int. J. Geo-Inf.*, 5, 103, <https://doi.org/10.3390/ijgi5070103>, 2016.
- KoBoToolbox: available at: <http://www.kobotoolbox.org/>, last access: 15 November 2016.

- Kreibich, H., Piroth, K., Seifert, I., Maiwald, H., Kunert, U., Schwarz, J., Merz, B., and Thieken, A. H.: Is flow velocity a significant parameter in flood damage modelling?, *Nat. Hazards Earth Syst. Sci.*, 9, 1679–1692, <https://doi.org/10.5194/nhess-9-1679-2009>, 2009.
- Kreibich, H., Botto, A., Merz, B., and Schröter, K.: Probabilistic, Multivariable Flood Loss Modeling on the Mesoscale with BT-FLEMO, *Risk Analysis*, 37, 774–787, <https://doi.org/10.1111/risa.12650>, 2016.
- Kundzewicz, Z. W., Krysanova, V., Dankers, R., Hirabayashi, Y., Kanae, S., Hattermann, F. F., Huang, S., Milly, P. C. D., Stoffel, M., Driessen, P. P. J., Matczak, P., Quevauviller, P., and Schellnhuber, H.-J.: Differences in flood hazard projections in Europe – their causes and consequences for decision making, *Hydrol. Sci. J.*, 62, 1–14, <https://doi.org/10.1080/02626667.2016.1241398>, 2017.
- Landkreis Schwäbisch Hall: Unwetter-Schadensliste, available at: [http://www.lrasha.de/index.php?id=302?&id=302?&no_cache=1&publish\[id\]=457120&publish\[start\]=](http://www.lrasha.de/index.php?id=302?&id=302?&no_cache=1&publish[id]=457120&publish[start]=), last access: 16 August 2016.
- Maiwald, H. and Schwarz, J.: Damage And Loss Prognosis Tools Correlating Flood Action And Building's Resistance-type Parameters, *Int. J. Safety Security Eng.*, 5, 222–250, <https://doi.org/10.2495/SAFE-V5-N3-222-250>, 2015.
- Maiwald, H. and Schwarz, J.: Die Sturzflut von Braunsbach – Ingenieuranalyse der Gebäudeschäden, *Bautechnik*, 93, 925–932, <https://doi.org/10.1002/bate.201600087>, 2016 (in German).
- Maksimović, Č., Prodanović, D., Boonya-Aroonnet, S., Leitão, J. P., Djordjević, S., and Allitt, R.: Overland flow and pathway analysis for modelling of urban pluvial flooding, *J. Hydraul. Res.*, 47, 512–523, <https://doi.org/10.1080/00221686.2009.9522027>, 2009.
- Merz, B., Kreibich, H., Schwarze, R., and Thieken, A.: Review article “Assessment of economic flood damage”, *Nat. Hazards Earth Syst. Sci.*, 10, 1697–1724, <https://doi.org/10.5194/nhess-10-1697-2010>, 2010.
- Milanesi, L., Pilotti, M., and Ranzi, R.: A conceptual model of people's vulnerability to floods, *Water Resour. Res.*, 51, 182–197, <https://doi.org/10.1002/2014WR016172>, 2015.
- Molinari, D., Menoni, S., Aronica, G. T., Ballio, F., Berni, N., Pandolfo, C., Stelluti, M., and Minucci, G.: Ex post damage assessment: an Italian experience, *Nat. Hazards Earth Syst. Sci.*, 14, 901–916, <https://doi.org/10.5194/nhess-14-901-2014>, 2014.
- Munich Re: Topics Geo 2016 – Natural catastrophes 2016 – Analyses, assessments, positions, München, 2017.
- Murawski, A., Zimmer, J., and Merz, B.: High spatial and temporal organization of changes in precipitation over Germany for 1951–2006, *International J. Climatol.*, 36, 2582–2597, <https://doi.org/10.1002/joc.4514>, 2015.
- Osberghaus, D. and Philippi, A.: Private Hochwasservorsorge und Elementarschadenversicherung – Moral Hazard, der Effekt von Informationskampagnen, und eine Versicherungssillusion, *ZVerswiss.*, 105, 289–306, <https://doi.org/10.1007/s12297-016-0341-2>, 2016 (in German).
- Papathoma-Köhle, M.: Vulnerability curves vs. vulnerability indicators: application of an indicator-based methodology for debris-flow hazards, *Nat. Hazards Earth Syst. Sci.*, 16, 1771–1790, <https://doi.org/10.5194/nhess-16-1771-2016>, 2016.
- Pierson, T. C. and Costa, J. E.: A rheologic classification of subaerial sediment-water flows, *Geol. Soc. America*, <https://doi.org/10.1130/REG7-p1>, 1987.
- Ripley, B. D.: *Pattern recognition and Neural Networks*, Cambridge University Press, Cambridge, 1996.
- Schelhorn, S. J., Herfort, B., Leiner, R., Zipf, A., and De Albuquerque, J. P.: Identifying Elements at Risk from OpenStreetMap: The Case of Flooding, *ISCRAM Conference Paper – University Park, Pennsylvania, USA, May 2014*.
- Schwarz, J. and Maiwald, H.: Prognose der Bauwerksschädigung unter Hochwassereinwirkung, *Bautechnik*, 84, 450–464, 2007 (in German).
- Song, L., Langfelder, P., and Horvath, S.: Random generalized linear model: a highly accurate and interpretable ensemble predictor, *BMC Bioinformatics*, 14, 1471–2150, 2013.
- Thieken, A. H., Müller, M., Kreibich, H., and Merz, B.: Flood damage and influencing factors: New insights from the August 2002 flood in Germany, *Water Resour. Res.*, 41, 1–16, <https://doi.org/10.1029/2005WR004177>, 2005.
- Thieken, A. H., Cammerer, H., Dobler, C., Lammel, J., and Schöberl, F.: Estimating changes in flood risks and benefits of non-structural adaptation strategies – a case study from Tyrol, Austria, *Mitig Adapt Strateg Glob Change*, 21, 343–376, <https://doi.org/10.1007/s11027-014-9602-3>, 2016a.
- Thieken, A. H., Kienzler, S., Kreibich, H., Kuhlicke, C., Kunz, M., Mühr, B., Müller, M., Otto, A., Petrow, T., Pisi, S., and Schröter, K.: Review of the flood risk management system in Germany after the major flood in 2013, *Ecol. Soc.*, 21, 51, <https://doi.org/10.5751/ES-08547-210251>, 2016b.
- Totschnig, R., Sedlacek, W., and Fuchs, S.: A quantitative vulnerability function for fluvial sediment Transport, *Nat. Hazards*, 58, 681–703, <https://doi.org/10.1007/s11069-010-9623-5>, 2011.
- Varnes, D. J.: *Landslide hazard zonation: A review of principles and practices*, UNESCO Nat. Hazard Ser., 3, 63, Paris, 1984.
- Vaz, E. and Arsanjani, J. J.: Crowdsourced mapping of land use in urban dense environments: An assessment of Toronto, *The Canadian Geographer/Le Géographe canadien*, 59, 1–10, <https://doi.org/10.1111/cag.12170>, 2015.
- Venables, W. N. and Ripley, B. D.: *Modern Applied Statistics with S*, Fourth Edition, Springer, New York, <https://doi.org/10.1007/978-0-387-21706-2>, 2002.
- Vogel, K., Laudan, J., Sieg, T., Rözer, V., and Thieken, A.: Data collection for a damage assessment after the flash flood in Braunsbach (Germany) in May 2016, *GFZ Data Services*, <https://doi.org/10.5880/figeo.2017.015>, 2017a.
- Vogel, K., Öztürk, U., Riemer, A., Laudan, J., Sieg, T., Wendi, D., Agarwal, A., Rözer, V., Korup, O., and Thieken, A.: Die Sturzflut von Braunsbach am 29. Mai 2016 – Entstehung, Ablauf und Schäden eines “Jahrhundertereignisses”, Teil 2: Geomorphologische Prozesse und Schadensanalyse, *Hydrologie & Wasserbewirtschaftung*, 61, 163–175, https://doi.org/10.5675/HyWa_2017.3_2, 2017b (in German).
- Volosciuk, C., Maraun, D., Semenov, V. A., Tilinia, N., Gulev, S. K., and Latif, M.: Rising Mediterranean Sea Surface Temperatures Amplify Extreme Summer Precipitation in Central Europe, *Scientific Reports*, 6, 32450, <https://doi.org/10.1038/srep32450>, 2016.

Yang, A., Fan, H., Jing, N., Sun, Y., and Zipf, A.: Temporal Analysis on Contribution Inequality in OpenStreetMap: A Comparative Study for Four Countries, *ISPRS Int. J. Geo-Inf.*, 5, 5, <https://doi.org/10.3390/ijgi5010005>, 2016.