Damage Prognosis of Dynamic Flood Events Using a System of Harmonized Damage Grades and Considering Uncertainties

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ABSTRACT

The “century flood events” of 2002, 2013 and 2021 in Germany show that extreme events with very low probabilities of occurrence are possible in a short time and can cause devastating damage. The events of 2002 and 2021 in particular indicated that, in addition to pure moisture damage, serious structural damage to the buildings could also occur.

Starting with the 2002 flood in Saxony, the Earthquake Damage Analysis Center (EDAC) at the Bauhaus-Universität Weimar has repeatedly carried out damage surveys after flood events over the past 20 years. The basis for the EDAC flood damage model was derived from the obtained damage cases.

In contrast to conventional flood damage models, the updated EDAC flood damage model allows not only the prediction of the financial losses, but also the prognosis of structural damage, including collapsed or even washed-away buildings. The analyses of the damage recordings after the flood of July 2021 in the federal states Rhineland-Palatinate and North Rhine-Westphalia also fall into this context.

The paper presents "fragility functions", which reflect the probability of exceedance of certain damage grades depending on water level and flow velocity. Using Monte Carlo simulations, these “fragility functions” also enable the identification of uncertainties in the prognosis of structural damage. In the past, these functions were successfully verified for low to moderate flow velocities during the 2002 flood in six investigation areas in the federal state of Saxony.

Evidence for high water levels in connection with high flow velocities has not been provided, yet. This article shows the verification of the derived “fragility functions” using the example of the extremely severe structural damage caused by the 2021 floods in the Ahr valley. The uncertainties of the prognosis can be expressed by selection of the mean or values for 50%, 84% or other fractile as starting points.

KEYWORDS: Vulnerability, types of structure, dynamic flood events, damage grades, fragility functions, Monte Carlo simulations, damage prognosis, scenarios

1 INTRODUCTION

The Earthquake Damage Analysis Center at the Bauhaus University Weimar (EDAC) has repeatedly conducted damage surveys immediately after flood events over the past 20 years, beginning with the 2002 floods in Saxony. The damage cases obtained in the process were used to derive the basis for the EDAC flood damage model (Maiwald and Schwarz, 2023). In this damage model, the elements of the European Macroseismic Scale 1998 (Grünthal et al., 1998) were applied to the natural hazard of flooding. The specific vulnerability of building types is considered by the assignment of vulnerability classes, depending on the materials of the load-bearing walls and the specific construction design. These vulnerability classes combine different building types with the same susceptibility to damage in an engineering-oriented approach (Schwarz and Maiwald, 2007).

In contrast to conventional flood damage models (see the overviews by Jongman et al., 2012; Gerl et al., 2016), the EDAC flood damage model allows the prognosis of structural damage, including collapsed or even washed-away buildings.

Analyses of the current damage assessments following the July 2021 floods in Rhineland-Palatinate and North Rhine-Westphalia also support this view. The event caused 184 casualties in Germany (134 in the Ahr Valley) and exceptionally high losses in the affected regions. Munich Re estimates total flood-related damages across Europe at €46 billion, with Germany alone accounting for €33 billion (Web-1). This means that the damage exceeds that caused by the floods of 2002, which amounted to €11.5 billion (Deutsche Rück, 2005) – equivalent to approximately €18.8 billion in 2021 prices based on the Federal Statistical Office's building price index (Statistisches Bundesamt, 2022). The 2021 floods were marked by exceptionally high inundation levels and flow velocities, causing severe structural damage to buildings and infrastructure, particularly in the Ahr Valley.

For the prognosis of structural damage, the EDAC flood damage model provides various vulnerability functions. They have been validated in different investigation areas in the Free State of Saxony based on the damage caused by the 2002 floods for low to moderate flow velocities (Maiwald and Schwarz, 2015, Maiwald et al., 2022a, Schwarz and Maiwald, 2008). Validation outside Saxony and for high flow velocities is still pending. A continuation of the analyses of damage survey following the floods in July 2021 in the Federal States of Rhineland-Palatinate and North Rhine-Westphalia (Maiwald et al., 2022b) enables a validation for a special type of fragility functions; results are given in the paper.

2 DATA

2.1 Damage Database

The damage database underlying the vulnerability and damage functions of the current version of the EDAC flood damage model is presented in detail in Maiwald et al (2022a). The unified compilation of damage cases is the result of an extensive review of damage data from the 2002 floods at the Saxonian Relief Bank. The database contains data from approximately 5,000 damaged buildings with the relevant structural parameters, the inundation levels, the descriptions of the structural damage and the actual recovery costs. For approximately 1,000 damage cases, hydraulic simulations of water levels were used to assign flow velocities. The calculated flow velocities do not exceed the value of $v_{fl} = 2.5$ m/s, meaning that a different data source had to be used for high flow velocities.

Therefore, to derive the vulnerability functions presented in Maiwald et al. (2022a) for the prognosis of the expected value of structural damage and the fragility functions validated here, damage data from the tsunami caused by the Tohoku earthquake (2011) were also used covering high inundation levels and flow velocities (cf. Suppasri et al., 2013). Further explanations on the data background of fragility functions can also be found in Maiwald and Schwarz (2022).

2.2 Field Survey of the 2021 Flood

Based on and continuing similar operations, researchers of EDAC carried out several damage surveys in the Ahr Valley in Rhineland-Palatinate between July 19 and August 5, 2021 (Figure 1). The objective was the documentation of damage to affected building stock. In addition to the elaboration of observed damage patterns, relevant building characteristics and structural parameters (e.g., building use, number of stories, inlet heights, wall construction type, basement configuration, roof structure) were collected on site or subsequently assigned during plausibility checks and data enhancement, following the system developed in Schwarz et al. (2019). Consistent with the EDAC flood damage model (Maiwald and Schwarz, 2023), each damage case was classified into a corresponding damage grade, representing the extent of structural damage (cf. Section 3.1). In total, damage cases ranging from light structural damage to collapsed or washed-away buildings caused by high inundation levels and flow velocities in combination with bank erosion and foundation scouring contribute to a significant extension of the database.

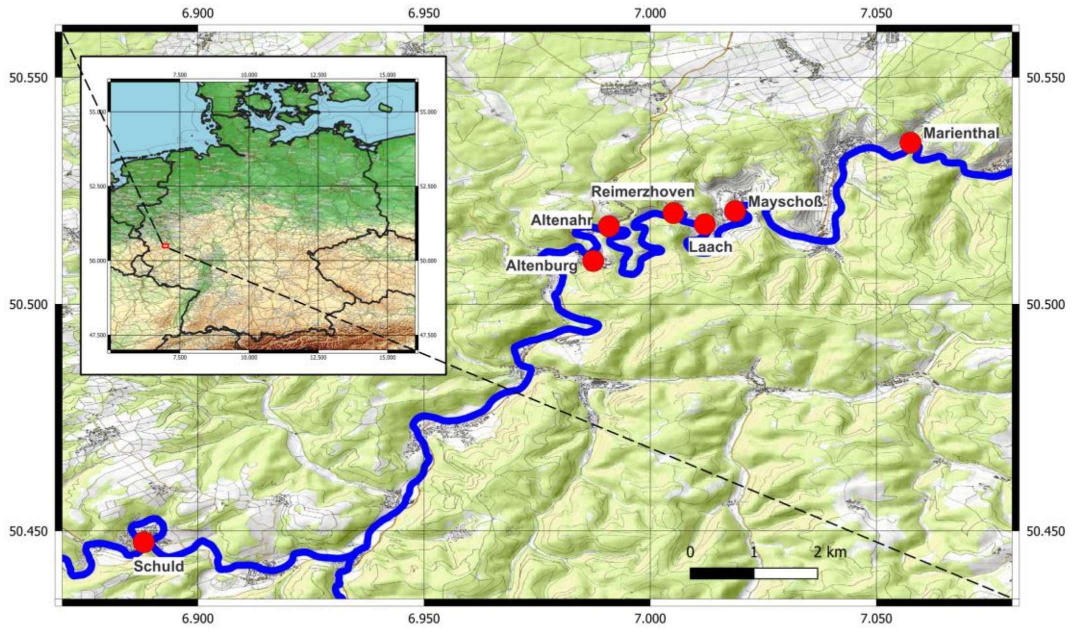


Figure 1: Investigation areas of the 2021 flood in the Ahr Valley (Basemap: OpenTopoMap)

A detailed evaluation of the collected building and damage data can be found in Maiwald et al. (2022b). The documented building data form the basis of the resistance parameters for the simulations in Section 4.

2.3 Flood Scenario

As part of a scientific collaboration directed to the re-interpretation of the flood scenario for the 2021 floods in the Ahr Valley the hydrodynamic model calculated using the RIM2D (Apel et al., 2022) has been made available for this study. The program offers the modelling of pluvial (rain-induced) and fluvial (river) floods in urban and rural areas. It uses graphics processing units (GPUs) for fast and efficient calculations, enabling rapid simulation of flood dynamics. This makes it suitable for advanced applications such as probabilistic flood risk analysis and operational flood forecasting.

Background of the simulation is the official Digital Elevation Model (DEM 10 m resolution: © GeoBasis-DE/BKG 2012). The model used in the paper consists of two sections: Müsch to Altenahr and from the Altenahr gauge to Sinzig. In the investigation areas, the model was further adapted to the actual existing structures. The water levels (h_{gl}) and flow velocities ($_{vfl}$) determined from the Grid files were assigned to the buildings in QGIS. Since there are no impact values in the grids calculated in the areas of the building floor plans themselves, a 5 m buffer was placed around the structures and the mean values for h_{gl} and v_{fl} were calculated in the buffer areas. In the investigation areas, high inundation levels of up to 8 m and high flow velocities of more than 9 m/s were calculated for individual buildings. These values are applied as impact parameters for the simulative flood damage modelling in Section 4.

3 ELEMENTS OF THE EDAC FLOOD DAMAGE MODEL

3.1 Damage Grades

Based on the documented building stock and building damage in August 2002, Schwarz and Maiwald (2007) introduced an initial five-stage differentiation of damage grades ranging from simple moisture penetration (D1) to complete collapse of the building (D5). In Maiwald and Schwarz (2019), this damage scale was extended by an additional damage grade D6 in order to distinguish between buildings that were washed away or displaced from their foundations and collapsed buildings (D5).

Table 1: Applied flood damage scale (complete description c.f. Maiwald and Schwarz, 2019)

Damage grade		**D1**	**D2**	**D3**	**D4**	**D5**	**D6**
Damage	structural	none	light	moderate	heavy	very heavy	complete
	non-structural	light	moderate	heavy	very heavy	very heavy	complete

The six-stage damage scale (Table 1) represents one of the basic elements of the EDAC flood damage model (Maiwald and Schwarz, 2023).

3.2 Vulnerability Classes

The concept of vulnerability classes refers to the European Macroseismic Scale EMS-98 (Grünthal et al., 1998); it is one of innovative aspects to classify the observed shaking effects of higher earthquake intensities systematically on the basis of damage pattern for pre-classified types of structures (buildings). The vulnerability classes summarize building types that exhibit similar structural damage under comparable impact intensity (see Table 2). Schwarz and Maiwald (2007) successfully adapted this concept to flood damage and risk assessment; an advance state in methodology, tool development and application is presented by Schwarz et al. (2018). The Vulnerability Table (Table 2) is a key element of the EDAC damage model (Maiwald and Schwarz, 2023). Flood vulnerability class HW-A represents the most vulnerable building category, buildings of vulnerability class HW-F are expected to withstand even high impact levels with minimal or no significant structural damage (Maiwald et al., 2022a).

Table 2: Classification of building types into vulnerability classes (Schwarz et al., 2018)

Building type	**Flood vulnerability class HW-**					
	A	**B**	**C**	**D**	**E**	**F**
Clay	○					
Prefabricated timber frame	|—	○	—|			
Timber frame with masonry or clay infills	|—	○	···|			
Masonry	|···	···—	○	···|		
Reinforced concrete			|···	○		
Flood resistant design				|—	○	
Flood evasive design						○

○ Most likely vulnerability class — Probable range ··· Range of less probable, exceptional cases

4 SIMULATIVE FLOOD DAMAGE MODELLING

4.1 Fragility Functions for Dynamic Floods Considering Water Level and Flow Velocity

The EDAC flood damage model (Maiwald and Schwarz, 2023) provides different types of vulnerability functions for calculating the expected Mean damage grade (D_m). The term fragility functions mean functions with which the probability of exceedance a certain damage grade D_i can be determined depending on the intensity of impact. In general, the cumulative logarithmic normal distribution (Eqn. 1) is used to describe the functions mathematically.

$F_{Di}(x)$ is the conditional probability that the structure will reach or exceed the damage grade D_i, depending on the action parameter x. The parameters μ and σ are to be derived for each building type, vulnerability class and damage grade. From Eqn. (2) the probability that a building will be damaged up to the damage grade D_i is calculated.

$$F_{D_i}(x) = \Phi\left(\frac{\ln(x) - \mu}{\sigma}\right) \tag{1}$$

$$P\left[D_i \mid x\right] = F_{D_i}(x) - F_{D_i+1}(x) \tag{2}$$

x - impact parameter ($x = h_{gl} + h_{gl} \cdot v_{fl}^2$), not true in units

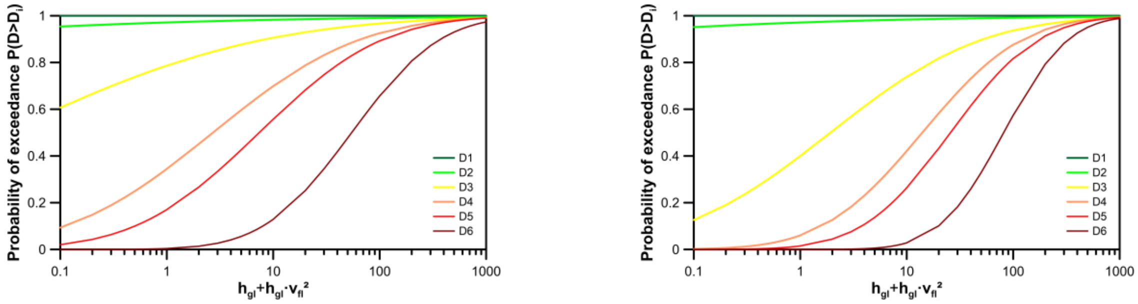
h_{gl} - waler level above ground level

μ - logarithmic mean

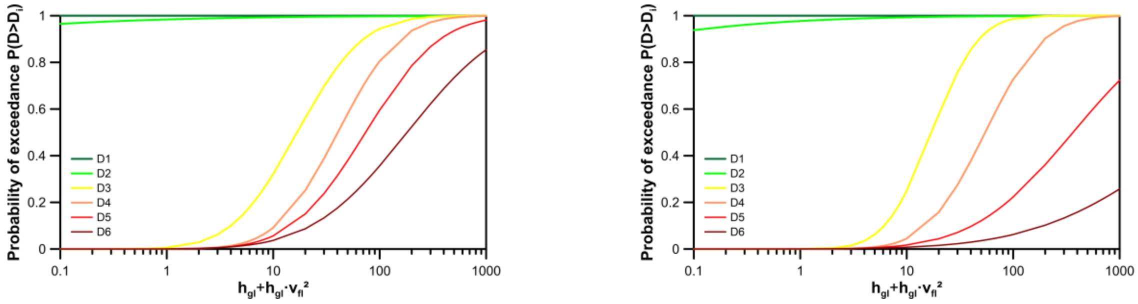
Φ - standard normal distribution

v_{fl} - flow velocity

σ - logarithmic standard deviation



a) HW-A b) HW-B



c) HW-C d) HW-D

Figure 2: Fragility function considering water level and flow velocity (Maiwald and Schwarz, 2022)

The fragility functions for vulnerability classes (Figure 2) used in this study were first presented in Maiwald and Schwarz (2022) and validated for six Saxon investigation areas for low and moderate flow velocities. The parameter $x = h_{gl} + h_{gl} \cdot v_{fl}^2$, has been proven as an effective impact factor. Preliminary and successful application of the fragility functions in the Ahr Valley - limited to the investigation areas of Altenburg and Altenahr and using a different hydraulic model - can be found in Schwarz et al. (2023).

Table 3 lists the fragility function control parameters. Preliminary and successful application of the fragility functions in the Ahr Valley - limited to the investigation areas of Altenburg and Altenahr and using a different hydraulic model - can be found in Schwarz et al. (2023).

Table 3: Control parameter of the fragility functions (Maiwald and Schwarz, 2023)

Damage Grade	HW-A		HW-B		HW-C		HW-D	
	μ	σ	μ	σ	μ	σ	μ	σ
D2	-20.00	10.50	-18.05	9.49	-15.00	7.00	-10.00	5.00
D3	-3.50	4.40	0.65	2.58	2.82	1.12	2.84	0.80
D4	1.00	2.50	2.64	1.70	3.70	1.05	4.00	1.00
D5	2.00	2.10	3.25	1.50	4.30	1.26	5.90	1.70
D6	4.00	1.50	4.40	1.10	5.20	1.62	8.60	2.60

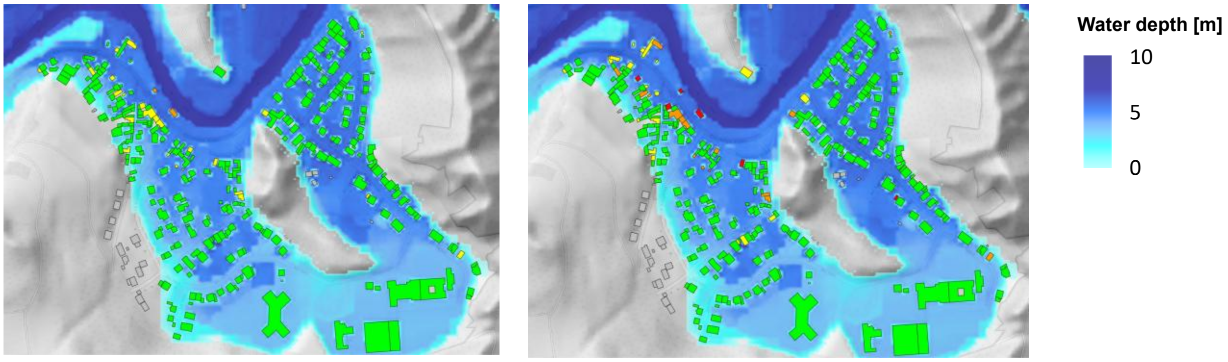
4.2 Application to 2021 Flood in the Ahr Valley

For the re-interpretation of the observed damage, the flood-damage simulation methodology based on the fragility functions presented in Section 4.1 is applied. The mean values for the water level and the flow velocity on each building are considered. Structural damage is simulated by generating 1,000 random realizations using a Monte Carlo approach. This simulation-based approach enables the quantification of the probable scatter of the structural damage. Table 4 provides the outcome of error analysis for residential buildings in each of the investigation areas in the Ahr Valley in terms of the Mean Error (ME), the Mean Absolute Error (MAE), and Root Mean Square Error (RMSE).

Table 4: Error analysis of the simulations for residential buildings

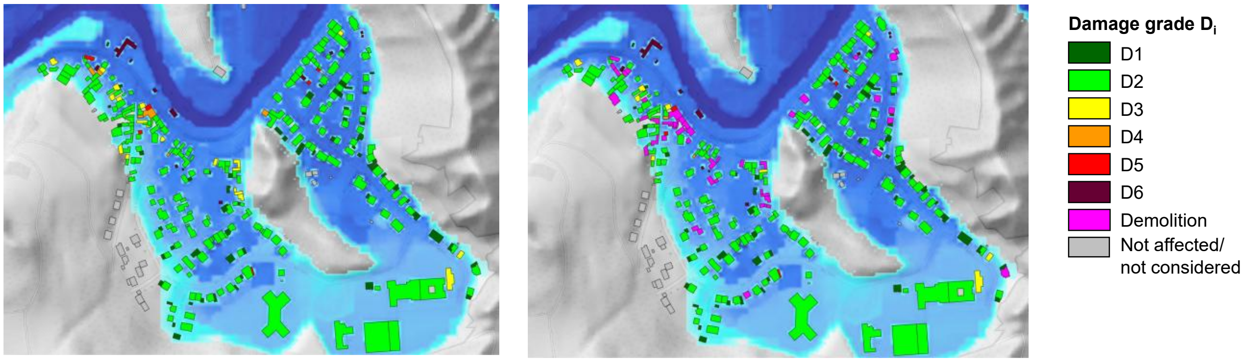
Investigation area	No.	50 % fractile			84 % fractile			Mean		
		ME	MAE	RMSE	ME	MAE	RMSE	ME	MAE	RMSE
Altenahr	59	0.49	0.73	1.24	0.19	0.69	1.14	0.40	0.71	1.14
Altenburg	171	0.05	0.15	0.47	-0.07	0.21	0.57	0.00	0.19	0.44
Laach	43	0.26	0.44	0.85	-0.37	0.70	1.06	0.09	0.51	0.78
Marienthal	43	0.42	0.51	1.03	0.19	0.56	1.06	0.29	0.53	0.98
Mayschoß	146	-0.10	0.30	0.71	-0.31	0.46	0.95	-0.13	0.35	0.70
Reimerzhoven	23	-0.48	0.48	0.81	-1.00	1.00	1.37	-0.50	0.55	0.78
Schuld	138	-0.33	0.62	1.00	-0.76	0.96	1.40	-0.41	0.70	0.98
Combined	623	**-0.01**	0.40	0.83	-0.29	0.57	1.04	**-0.08**	0.45	0.80

The maps in the Figures 3 and 4 give insight in the simulated 50% and 84% fractiles of the damage grades in Altenburg and Mayschoß. For comparison maps for observed damage grades are given. Results follow the studies by Maiwald et al. (2022b) to support the pending planning decisions.



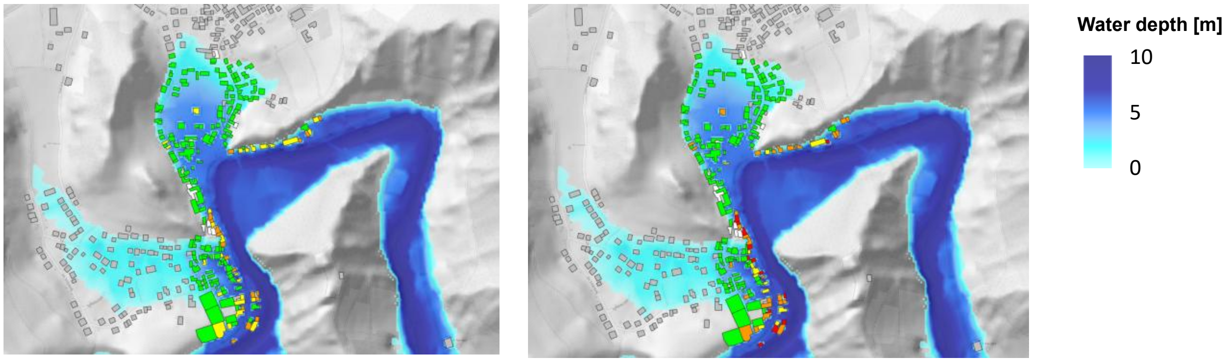
a) 50% fractile

b) 84% fractile

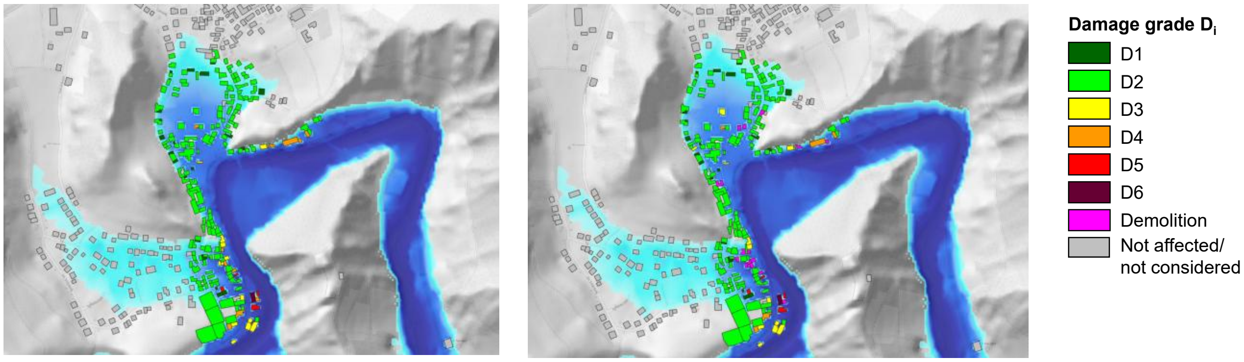


c) Observed damage d) Observed damage, incl. demolitions

Figure 3: Comparison of simulated and observed damage grades for the investigation area Altenburg



a) 50% fractile b) 84% fractile



c) Observed damage d) Observed damage, incl. demolitions

Figure 4: Comparison of simulated and observed damage grades for the investigation area Mayschoß

5 CONCLUSIONS AND OUTLOOK

As it can be concluded from Table 4, the 50% fractiles and mean values show the lowest ME values. In general, the slight over- and underestimations in the investigation areas indicate a remarkable prognosis quality. As the low ME values in the "combined" row show, the deviations balance each other out across the entire area. The RMSE values for the entire area are almost twice as high as the values determined for the Saxon investigation areas in Maiwald et al. (2022a). And the MAE values for the entire area are only slightly higher (10 – 15%). Recognizing that the uncertainties (in hydraulic modelling and in the assignment of structural parameters) will remain, the results are encouraging. Not at least, it has to be emphasized that the damage model was derived from empirical data from other flood affected regions and that extremely high flow velocities occurred 2021 in the Ahr Valley. Figures 3 and 4 show also a good visible spatial correlation between the 50% fractiles of the simulated and the observed damage. It is noteworthy that the later demolitions are partially reflected in the 84% fractile values.

The initial results of the investigations in the Ahr Valley confirm the effectiveness and transferability of the vulnerability-oriented approach for the prognosis of structural damage caused by extreme flooding events. As demonstrated by Maiwald and Schwarz (2022), realistic prognosis of financial losses can also be generated, along with estimates of the expected ranges of scatter.

Due to the sensitivity of the topic and the non-availability of reliable data on the actual losses for the individual investigation areas in the Ahr Valley, any comparison between the simulated losses (including their ranges of scatter) and the observed losses will have to be deferred to subsequent studies.

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