SIMULATIVE FLOOD DAMAGE MODELLING TAKING INTO ACCOUNT INUNDATION LEVEL AND FLOW VELOCITY: UNCERTAINTIES AND STRATEGIES FOR FURTHER REFINEMENT

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ABSTRACT
In recent years, floods in Germany have caused billions of Euros in property damage. As part of the project "Innovative Vulnerability and Risk Assessment of Urban Areas against Flood Events" (INNOVARU), a realistic, practical model for the monetary assessment of potential flood damage to residential building stock was developed, which also allows the prognosis of structural damage. The structural damage can be predicted in the form of mean damage grades using vulnerability functions, which take into account the vulnerability of the different building types depending on the inundation level and flow velocity. So far, the scatter in the damage has not been taken into account. The paper presents "fragility functions" which enable the quantification of the exceedance probability of certain damage grades depending on inundation level and flow velocity. These functions allow the identification and implementation of the scatter of structural damage. They also enable a simulative damage prognosis using the Monte Carlo method, which provides the basis for loss calculations and serve to quantify the scatter within the financial loss indicators. This can introduce a new level of cost–benefit analyses for the planning of new flood protection measures. For lower flow velocities, typical for river floods, the study is based on a comprehensive qualified damage dataset compiled after the 2002 flood in Germany. The lack of reliable damage data caused by high flow velocities during flash flood events is compensated by an innovative approach. For this purpose, damage data from the tsunami of the Tohoku earthquake in Japan in 2011 are re-evaluated and included in the analysis. The developed "fragility functions" are applied to the re-interpretation of the August 2002 flood damage and loss in six different study areas in the Free State of Saxony. An outlook to the application for flash flood events is given.
Keywords: structural damage, damage prognosis, flow velocity, vulnerability classes, fragility functions, validation, simulation, scatter.

1 INTRODUCTION

The recent flood events in Germany (2002, 2010, 2013, 2021) show that even extreme events with very low probabilities of occurrence are possible and can result in devastating damage. The floods in 2002 and 2021 especially, have shown that in addition to pure penetration damage severe structural damage up to total destruction of the building substance could occur. Conventional flood loss models cannot consider this type of damage in an adequate way. An overview of such models is given in Jongman et al. [1].

Structural damage has mostly been examined in the past in terms of total failure of the structure depending on the influence of the flow velocity in connection with the water level [2], [3] or additional criteria for a partial failure are determined [4]. A refined differentiation to take into account the different damage patterns of structural damage, the conversion into concrete losses and the consideration of the scatter in the damage with comparable effects are missing in these studies.

The flood damage model developed at the Earthquake Damage Analysis Center (EDAC) of the Bauhaus-Universität Weimar provides with the derived vulnerability functions a first

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attempt to predict the structural damage in the form of mean damage grades depending on the building types, water level and specific energy height [5], [6].

The latest enhancements of the flood damage model refer to the insights from the project "Innovative Vulnerability and Risk Assessment of Urban Areas against Flood Events – INNOVARU", funded by the German Federal Ministry of Education and Research (BMBF). The aim of the project was the development of an application-ready model for the monetary assessment of the expected flood damage on the existing building stock and the decision and flood risk management support for the Free State of Saxony. The final approach is combining the advantages of the empirically supported prognosis of structural damage with the flexibility of building typological synthetic damage functions for loss estimations (cf. [7], [8]). As part of the sub-project processed by the EDAC, a set of refined functions for the prognosis of the structural damage is developed taking into account new combinations of water level, flow velocity and the building vulnerability, which are presented in Maiwald et al. [9], [10]. First results of the complete procedure developed in INNOVARU can be taken from Golz et al. [11].

Another result of the project are fragility functions with which the probability of exceedance for each damage grade can be determined. The new functions will be presented in the paper and applied to different study areas in Saxony on a microscale level for the 2002 flood.

2 BASIC ELEMENTS OF SIMULATIVE DAMAGE MODELING

2.1 Damage database

2.1.1 EDAC flood damage database

The EDAC flood damage database is the result of a comprehensive evaluation of damage caused by the 2002 flood in Saxony. Out of the 22,554 cases of flood-induced damage processed by the Saxonian Relief Bank (SAB) [12], detailed damage reports were available for around 8,000 buildings. Approximately 5,000 damage reports were accessed, analysed and entered into the database. In addition to the relevant building parameters and the inundation levels, the descriptions of the structural damage and the actual recovery costs were evaluated.

Based on hydraulic calculations (see also Section 2.3), estimated flow velocities were assigned to the individual damage cases ($n \approx 1{,}000$) for four selected study areas in Saxony [13]. It has to be emphasized that the data in the EDAC flood damage database, for which flow velocities could be assigned, generally relate to damage cases with moderate flow velocities ($v_{max} \approx 2.5$ m/s) typical for river floods.

Reliable data for damage due to higher flow velocities (such as flash flood events) or the flow velocities for related damage cases contained in the database are currently not available. For this reason, an innovative approach is chosen to expand the damage database by including damage data from the 2011 Tohoku earthquake induced tsunami in Japan.

2.1.2 Tsunami damage data

A comprehensive damage database ($n \approx 252{,}000$) is available for the tsunami after the 2011 "Tohoku earthquake" in Japan [14]. Based on this database, fragility functions for the tsunami hazard are derived in Suppasri et al. [15], [16] depending on the water level h on the building. Six damage classes were defined in analogy to the scheme of the European Macroseismic Scale EMS-98 [17] for earthquake shaking effects.

The damage classification proposed in Suppasri et al. [15], [16] was taken into account in Maiwald and Schwarz [18] to derive unified damage scales for the main natural hazard types. The database was re-evaluated in Maiwald and Schwarz [19] in order to develop a mathematically based methodology for deriving a vulnerability table of buildings (comparable to EMS-98) for tsunami impact. This leads to the assignment of vulnerability classes to the building types from the tsunami damage database. In addition, the flow velocities were estimated with respect to the coastal type (ria or plain coast).

2.2 Knowledge of building stock

For the INNOVARU project, the towns of Pirna, Grimma and Freital in the Free State of Saxony (in Germany) were selected as study areas. The parameters of the building stock of the towns of Döbeln, Eilenburg, Grimma and Flöha are available from previous research EDAC projects on a detailed microscale level. In the study areas, the entire building stock affected by the 2002 flood was systematically investigated on site; the relevant building parameters [20] and the existing flood marks were documented. The building stock of Pirna was analysed in Naumann and Rubin [7] and Naumann et al. [8], from one of the INNOVARU project partner. The building stock of the town Freital was documented within the INNOVARU project. The geographical location of the flood-affected areas considered in this paper can be taken from Fig. 1.

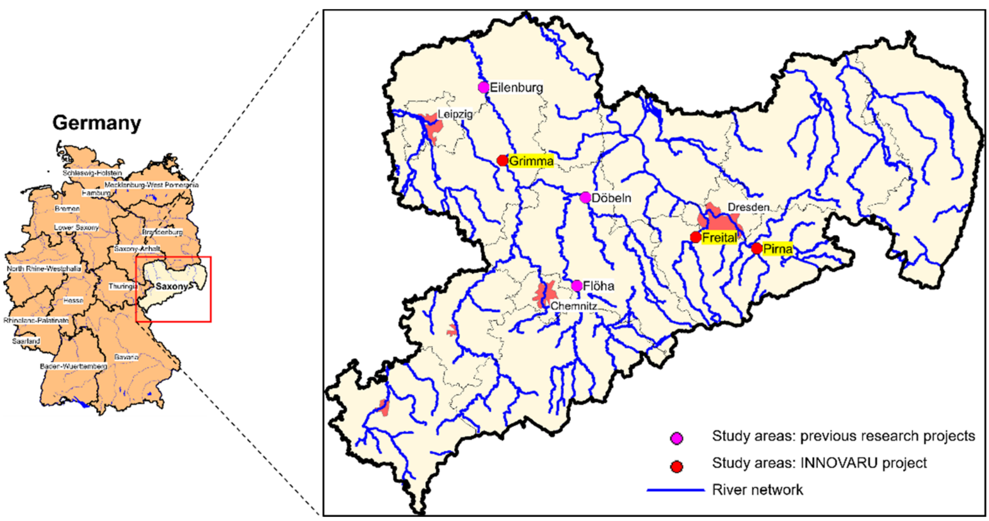

Figure 1: Study areas in the Free State of Saxony.

2.3 Flood scenarios

The improved methods in the paper will be validated against the damages of the 2002 flood in the study areas. The required inundation levels and flow velocities at the damaged buildings can be assigned (although only approximately) through a subsequent hydraulic simulation of the flood event. The influence of flow velocity on damage lead to the conclusion that very detailed 2D hydraulic models are necessary.

Such accurate models are available for the INNOVARU study areas of Freital, Grimma, Pirna and also for the town of Döbeln. For Eilenburg and Flöha, the flow around building stock is simplified considered over a mean roughness. The hydraulic calculations for the study areas of Grimma and Flöha are available from the Risk Management of Extreme Flood Events (RIMAX) project Methods for the Evaluation of Direct and Indirect Flood Losses (MEDIS) in which also the flow velocities for Eilenburg were derived [21]. The INNOVARU project comprises the re-interpretation of the 2002 flood event in the study area of Freital. 2D unsteady flow modelling was performed. For the 2002 flood in Pirna, a hydraulic calculation for the Elbe flood is available (Dam Authority Saxony).

In order to consider the upstream flooding from the tributaries Gottleuba and Seidewitz for the re-interpretation of the damage in the study area, the scenario HQ 100 (which shows a good match with the official inundation areas due to the 2002 flood) was assumed. Further information on the hydraulic models used within the INNOVARU project can be taken from Maiwald et al. [10]. In the course of further investigations, uncertainties considerations in the prognosis of the hydraulic action parameters would also have to be considered (cf. [22]).

3 VULNERABILITY OF BUILDINGS AND FLOOD DAMAGE

3.1 Damage scale for flooding

Based on the building stock and documented damage to buildings in August 2002, an initial five-stage differentiation of damage grades was implemented in Schwarz and Maiwald [23]; it represents one of the basic elements in the EDAC flood damage model [5].

The research on the vulnerability and risk assessment of buildings under extreme natural hazards in the sense of a multi-hazard approach [19], [20], also led to a further development into a six-graded damage scale in Maiwald and Schwarz [18] to include cases of severe damage in which buildings tipped over, were displaced from their foundations or washed away completely (cf. Table 1). In addition, washing out effects have to be considered in the description of damage grades.

Considering the observations during the March 2011 tsunami in Japan [15] and the tsunami damage analysed by EDAC after the 2010 Maule earthquake in Chile [24], a damage grade D6 (cf. Table 1) is introduced in Maiwald and Schwarz [18] in order to delineate these extreme cases of damage from the grade for common collapse (D5).

The introduction of D6 makes the identification of failure mechanisms comprehensive. In financial terms, both damage grades D5 and D6 are similar and represent a total loss. However, there are also differences that still need to be analysed. At the current state of the investigations, it can be assumed that additional demolition and disposal costs have to be taken into account for D5, but they do not apply for D6 if buildings are washed away.

3.2 Flood vulnerability classes

The concept of vulnerability classes was developed for determining earthquake intensity and observed shaking effects in the EMS-98 [17]. This concept was successfully transferred to flood hazard and damage interpretation by Maiwald and Schwarz [23] and further developed in Schwarz et al. [25].

Vulnerability classes subsume the event-specific vulnerability (or resistance) in the form of occurrence of similar damage grades (in quantity and quality) under the same impact intensities; they combine structures of comparable vulnerability in classes. The presented

Table 1: Enhanced flood damage scale (according to Maiwald and Schwarz [18]; an extension of Schwarz and Maiwald [23]).

Damage grade	Damage		Description
	Structural	Non-structural	
D1	None	Light	Only wetting through, dirt
D2	Light	Moderate	Slight cracking to loadbearing walls Doors/windows pushed in Washing out of foundations *Replacement of finishings necessary* *Contamination*
D3	Moderate	Heavy	Larger cracking in loadbearing walls and slabs Settlement Collapse ore of non-loadbearing walls *Replacement of non-loadbearing building elements necessary*
D4	Heavy	Very heavy	Collapse of loadbearing walls, slabs *Replacement of loadbearing walls, slabs*
D5	Very heavy	Very heavy	Collapse of larger parts of building
D6	Complete	Complete	Dislocation: building completely washed away, toppled or displaced from foundation

vulnerability tables for earthquakes [17], floods and wind [25] contain four vulnerability classes (A to D) for the typical building stock and two classes (E and F) for buildings specially designed to withstand the corresponding natural hazard. Flood vulnerability class HW-A (typical for clay buildings, cf. Table 2) represents the most vulnerable buildings with the largest expected flood impact damage; the buildings of vulnerability class HW-F (introduced in Schwarz et al. [25]) should survive a strong impact level without significant damage [10].

Table 2: Classification of building types into vulnerability classes [25].

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.

HW-E buildings usually consist of reinforced concrete or masonry structures and follow a flood resistant design; they are characterized by the separation of the main building from the flood impact (for instance, by raising the ground floor onto storey-high columns). Vulnerability class HW-F is assigned to flood evasive designed constructions like floating homes (cf. [26]), and structural solutions especially adapted to floods. These buildings, erected on pontoons, float when the water level rises and thus avoid flooding. Steel or concrete is mostly used for the pontoons. The construction of the actual building is of minor importance since contact with the flood is limited to the pontoon. Due to the lack of corresponding damage data, these constructions are not considered in the investigations.

The scatter and uncertainty of the appropriate vulnerability class(es) for each building type are described as follows: most likely vulnerability class, probable range and range of less probable, exceptional cases. The most likely class and the range of scatter result from a variety of damage assessments (cf. Table 2). The specific classification within the range of scatter depends on the condition and the structural design of the building.

3.3 Loss prediction

In contrast to conventional damage models (see, e.g., overview in Jongman et al. [1]), the vulnerability-relevant building parameters are also considered in the loss prognosis within the existing EDAC flood damage model. Following the proposed methodology, a set of specific damage functions (SDFs) for loss predictions were presented in Maiwald and Schwarz [5], [6], [13], [27]. Functions refer to the building type (SDF Type 1a) or flood vulnerability class (SDF Type 1b). A second type of functions (SDF Type 2) transfers the calculated damage grades D_i into losses.

The SDFs of the EDAC flood damage model could be successful validated based on the actual reported losses of the 2002 flood on residential buildings [12] in the study areas of Döbeln, Grimma and Flöha in Saxony [6], [27]. Additionally, also the results for the losses based on improved methods for the prognosis of the structural damage presented in Maiwald et al. [10] show a good agreement with the observed losses of the 2002 flood in all of the considered study areas [9]. In the current study, the functions of SDF Type 2 [27] are applied.

4 SIMULATIVE FLOOD DAMAGE MODELING AND VALIDATION

4.1 Elements of the uncertainty chain

Various elements of the uncertainty chain can be taken into account in a simulative flood damage modelling: uncertainties on the impact side (water level, flow velocity), uncertainties in the description of the existing structure (location, vulnerability class and replacement values), uncertainties in the development of structural damage (fragility functions) and the scatter in the losses. Based on the water level as impact parameter in Schwarz et al. [28] the damage modelling considers the simulation of the structural damage and a simulative variation of the location of the building. The present study concentrates on the uncertainties in the prognosis of structural damage and the resulting losses depending on water level and flow velocity.

4.2 Fragility functions for floods considering water level and flow velocity

Fragility functions depending on the water level over the ground floor level were presented in Schwarz et al. [28]. In the INNOVARU project, two improved types of fragility functions were derived depending on the water level over ground level h_{gl} and flow velocity v_{fl}. Flow velocities from the hydraulic calculations were assigned to the flood damage data.

The flow velocities of the tsunami at selected points were estimated in Suppasri et al. [29] and Foytong et al. [30] using video recordings. In Suppasri et al. [29] the differences between Plain coast and Ria coast were also highlighted. The estimated flow velocities in Suppasri et al. [29] and Foytong et al. [30] enable the derivation of average values of the Froude number F_r according to the coast classification in order to approximate flow velocities for the damage data (cf. eqn (1) and [19]).

$$v_{fl} = F_r \cdot \sqrt{g \cdot h_{gl}} \,. \tag{1}$$

The term fragility functions (originating in earthquake engineering) means functions with which the probability of exceedance a certain damage grade can be determined depending on the magnitude of the impact [31]. In general, the cumulative logarithmic normal distribution (eqn (2)) is used to describe the functions mathematically.

$$F_{D_i}(x) = \Phi\left(\frac{\ln(x) - \mu}{\sigma}\right), \tag{2}$$

where x = impact parameter ($x = h_{gl} \cdot v_{fl}^2$ or $x = h_{gl} + h_{gl} \cdot v_{fl}^2$); Φ = standard normal distribution; μ = logarithmic mean; σ = logarithmic standard deviation; $F_{Di}(x)$ 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 (3) the probability that a building will be damaged up to the damage grade D_i is calculated:

$$P\left[D_i \mid x\right] = F_{D_i}(x) - F_{D_i+1}(x) \,. \tag{3}$$

It should be noted that the scatter of damage results from the probabilities of occurrence of the individual damage grades according to eqn (3) and not by the distribution function according to eqn (2). The approach known from earthquake engineering has been applied to the natural hazard tsunami in Suppasri et al. [16], Maiwald and Schwarz [19], and Suppasri et al. [29], and also seems to be expedient for the flood effects considered here. In general, the particularities of flood impacts compared to tsunami impacts must be taken into account. In case of a tsunami, the flow velocity according to eqn (1) is linked to the water level h_{gl}. This is much more complex in the event of a flood. Floods can only show a slight to standing water movement, even with high water levels.

In **approach 1**, the momentum flux $x = h_{gl} \cdot v_{fl}^2$ is examined as an impact parameter. Here, for very low or non-existent flow velocities ($v_{fl} \approx 0$), despite possible larger water level h_{gl}, the action parameter x is also 0. In order to compensate for this, in **approach 2** a not true to the unit combination of the two action variables $x = h_{gl} + h_{gl} \cdot v_{fl}^2$ is chosen. This has the advantage that at low flow velocities v_{fl} the impact parameter x is determined by the water level h_{gl}, while the flow velocity becomes dominant in the case of a highly dynamic flood.

Fig. 2 shows the probabilities of exceedance $P(D > D_i)$ of the combined damage data set for the vulnerability class HW-C (typical for masonry buildings). The plausible transition between the flood and tsunami damage data is clearly visible. The fragility functions can be derived from the combined data set using a non-linear regression. Fig. 3 displays the fragility functions of approach 2. For vulnerability class HW-A, engineering assumptions were made to estimate the control parameters, since the data coverage is currently still too low.

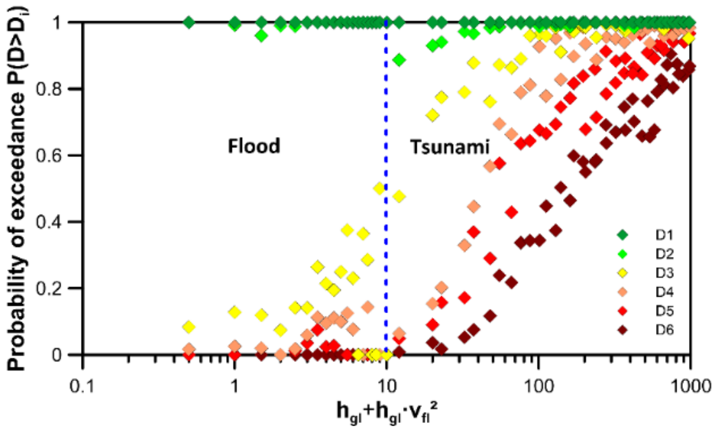

Figure 2: Probabilities of exceedance of the damage grades D_i for the vulnerability class HW-C (combined data set).

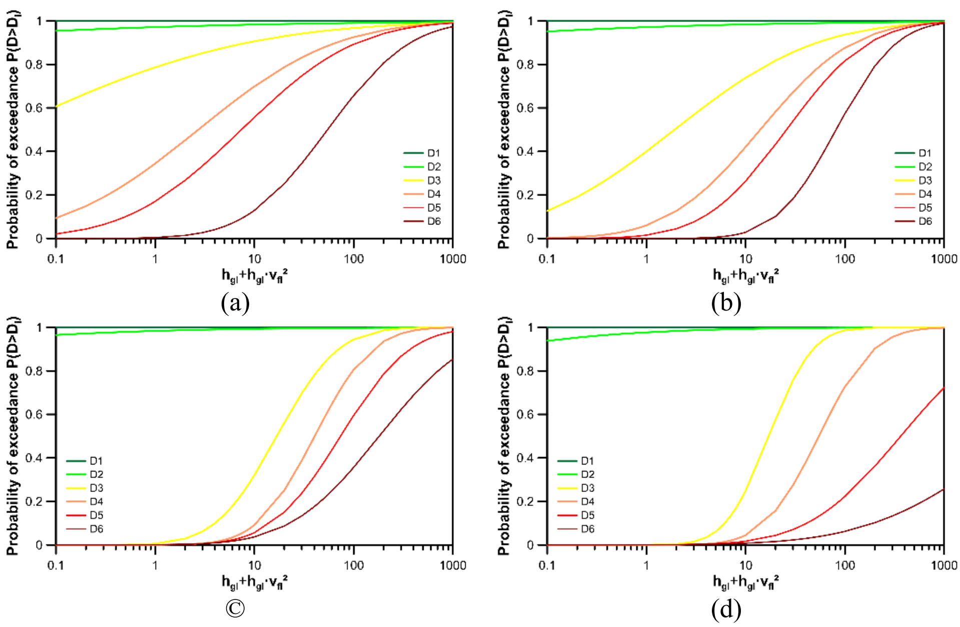

Figure 3: Fragility function of approach 2. (a) HW-A; (b) HW-B; (c) HW-C; and (d) HW-D.

4.3 Validation

The innovative options and advantages of the whole procedure are demonstrated by the case studies from the 2002 flood in Saxony. With the developed fragility functions, the probabilities of exceedance for the individual damage grades can be calculated for each individual building (microscale level) in the six study areas and towns of Saxony (Fig. 1).

The damage prognosis with the fragility functions also allows the transfer to financial loss indicators. A procedure for a Monte Carlo simulation was developed, which realises “n times” the damage grades according to the probability of exceedance according to the corresponding fragility functions. The losses are calculated for each of these damage grade realisations in the study areas, so that at the end n damage grade and loss scenarios are available.

Fig. 4 shows the comparison of the mean values of the losses for n = 1,000 simulations in comparison to the reported losses for the scenarios of the flood 2002. Both approaches show a good agreement with the actually reported losses for residential building stock (Fig. 4(a)), whereby the approach 2 results in a slightly better approximation. Underestimates (Eilenburg, Flöha, Freital, Grimma) but also overestimates (Döbeln, Pirna) of the real observed losses are possible here, so that there is no unique trend for the deviations.

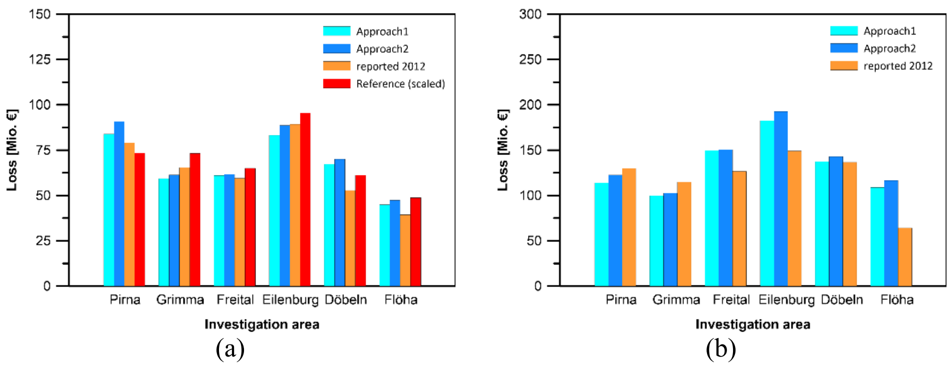

Figure 4: Comparison of the mean values of the losses (n = 1000 simulations) and the reported losses HW 2002 [12]. (a) Residential buildings; and (b) Entire building stock. Reported 2012: Final loss statement from the SAB [12]. Reference (scaled): Loss scaled to the number of residential buildings actually considered.

In areas with large industrial complexes (Eilenburg, Flöha), both approaches lead to a significant overestimation of the losses for the entire building stock (Fig. 4(b)). Individual case analyses would be necessary for such industrial complexes. But overall, the calculations can be approximated well to the losses that actually occurred. It can be stated that the newly developed method also delivers reliable results with regard to the prognosis of the expected values of the losses. A further improvement in the quality of the loss prognosis and a refinement in the consideration of the building parameters can be expected in future by application of the new developed building typological synthetic damage functions in Golz et al. [11].

The inconsistent trend in the deviations indicates the importance and the need to consider the uncertainties in the flood damage prognosis, in more detail. Fig. 5 shows the scatter of the losses for the residential building stock, which follows from n = 1000 Monte Carlo simulations according to approach 2. The mean value of the losses (cf. Fig. 4(a)), the ± 1σ standard deviation and also the reported losses of the SAB [12] are marked. (Note: For Grimma, actual losses are slightly outside the range shown.) For the residential building stock, the calculated standard deviations can be assessed as relatively low in the range of 1.0%–2.1%, while the overall range of scatter in the losses is between 8.2% and 11.6%.

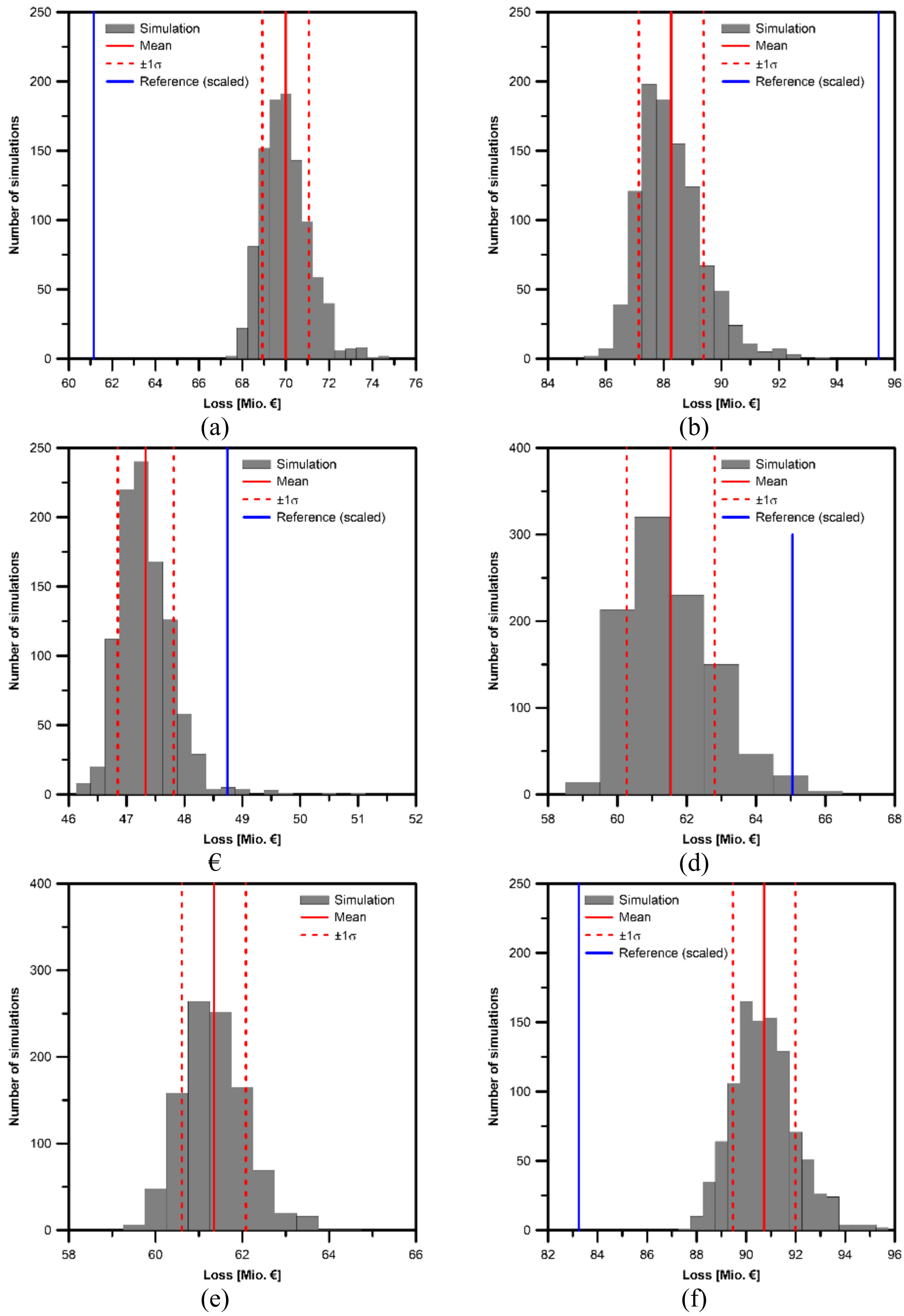

Figure 5: Calculated scatter of losses for residential building stock in the study areas (2002 flood) according to approach 2. (a) Döbeln; (b) Eilenburg; (c) Flöha); (d) Freital; (e) Grimma; and (f) Pirna.

Although the actually observed losses are mostly slightly outside of the calculated scatter range, it should be noted that the absolute deviation of the mean values is only approximately 10% on average, which is similar to the overall range of scatter in the losses. It has to be emphasized that these studies relate to one element of the uncertainty chain, only.

For this reason, other factors must also be taken into account in the future when describing the wide scatter of flood damage. The uncertainties or scatter that are "lost" when summarizing the range of variation which are related to the concrete construction/geometry and replacement value of the buildings and also the uncertainties which are related to the hydraulic scenarios [22] have not yet been considered. Other influencing factors have a random influence on the development of the damage (aleatoric uncertainties), but for technical and practical reasons they cannot be represented exactly in the prognosis model at present. These include, for example, the impact of debris, scouring and foundation erosion as well as unspecified contamination or pollution. The authors are convinced that the derivation and determination of certain probabilities of occurrence in connection with a Monte Carlo simulation offers possibilities for future consideration of these type of uncertainties.

5 CONCLUSIONS AND OUTLOOK

Considering the elements of the existing EDAC flood damage model, new approaches for the prognosis of the structural damages due to flood impact are developed in the paper. The presented model provides basic tools for the prediction of structural damage of the building including the scatter taking into account the specific building vulnerability, the inundation level and the flow velocity. The developed fragility functions represent an element for the consideration and identification of uncertainties in the flood damage and loss prognosis.

In this paper, a realistic re-interpretation of the real observed damages from the 2002 flood in Saxony is carried out. Results are presented for six different study areas with moderate flow velocities. Using the Monte Carlo method, the presented fragility functions enable a simulative prognosis of structural damage of the single buildings due to flood impact considering water level and flow velocity with two different approaches. The damage grades for n = 1,000 Monte Carlo simulations are calculated for each study area and converted into loss statements using the existing damage functions of the EDAC flood damage model. In addition to the expected values of the losses, the scatter range and uncertainties are also identified.

In all cases, a remarkably good agreement between the predicted and the reported losses can be stated for inventory of residential buildings, whereby approach 2 results in a slightly better approximation. A further improvement in the loss prognosis can be expected by the application of new synthetic damage functions that take into account the concept and engineered classification of the damage grades (as derived in the INNOVARU project [11]).

The derived new fragility functions enable in principle also damage prognosis for flash flood events with high flow velocities. Current investigations into the damage caused by the 2021 flood in the Ahr Valley in western Germany [32] are preparing the validation of the new approaches to such flood events.

With the fragility functions, a first element for considering the uncertainty chain is available, which initially lead to a relatively small scatter range in the loss prognosis. As target for the next step, the uncertainties of the building parameters, of the losses by the same damage grade, in the description of the impact parameter (water level, flow velocities, duration) and also aleatoric uncertainties would have to be considered. Taking into account the entire chain of uncertainty would offer new application possibilities in the context of cost–benefit studies. The previous approach in Germany, that cost/benefit ratios > 1 leads to the rejection of the measure, could be interpreted more generously in the future, for example if the costs of the measure lie within a scatter range of the damage prognosis that has to be defined.

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REFERENCES

[1] Jongman, B., Kreibich, H., Apel, H., Barredo, J.I., Bates, P.D., Feyen, L., Gericke, A. Neal, J., Aerts, J.C.J.H. & Ward P.J., Comparative flood damage model assessment: Towards a European approach. *Natural Hazards and Earth System Sciences*, **12**(12), pp. 3733–3752, 2012.

[2] Black, R.D., Floodproofing rural residences. Washington D.C. Report no EDA 77-088. US Department of Commerce, Economic Development Administration, 1975.

[3] Sangrey, D.A., Murphy, P.J. & Nieber, J.L., Evaluating the impact of structurally interrupted flood plain flows. Technical Report No. 98, Cornell University Water Resources and Marine Sciences Center, Ithaca, New York, USA, 1975.

[4] Clausen, L. & Clark, P.B., The development of criteria for predicting dambreak flood damages using modelling of historical dam failures. *International Conference on River Flood Hydraulics,* John Wiley & Sons Ltd, 1990.

[5] Maiwald, H. & Schwarz, J., Ermittlung von Hochwasserschäden unter Berücksichtitung der Bauwerksverletzbarkeit, EDAC-Hochwasserschadensmodell, Scientific Technical Reports 01-11, Universitätsverlag, Bauhaus-Universität Weimar, 2011.

[6] Maiwald, H. & Schwarz, J., Damage and loss prognosis tools correlating flood action and building's resistance-type parameters. *International Journal of Safety and Security Engineering*, **5**(3), pp. 222–250, 2015.

[7] Naumann, T. & Rubin, C., Ermittlung potenzieller Hochwasserschäden in Pirna nach dem gebäudetypologischen VERIS Elbe-Ansatz. *Tagungsband zum DWA-Seminar Hochwasserschadensinformationen: Neues und Bewährtes*, Hennef, pp. 86–101, 2008.

[8] Naumann, T., Golz, S. & Nikolowski, J., Synthetic depth-damage functions: A detailed tool for analyzing flood resilience of building types. *Final Conference of the COST action C22 Urban Flood Management in cooperation with UNESCO-IHP*, Paris, 2009.

[9] Maiwald, H., Kaufmann, C., Langhammer, T. & Schwarz, J., A new model for consideration of flow velocity in flood damage and loss prognosis. *FLOODrisk 2020 – 4th European Conference on Flood Risk Management*, Paper 11_9, 2021.

[10] Maiwald, H., Schwarz, J., Kaufmann, C., Langhammer, T., Golz, S. & Wehner, T., Innovative vulnerability and risk assessment of urban areas against flood events: Part 1 – Prognosis of structural damage with a new approach considering the flow velocity. *Natural Hazards* (accepted for publication), 2022.

[11] Golz, S., Maiwald, H., Naumann, T., Schwarz, J., Innovative vulnerability and risk assessment of urban areas against flood events: Part 2 – Prognosis of losses with a new approach for synthetic damage functions. *Natural Hazards* (forthcoming), 2022.

[12] Sächsische Aufbaubank/Saxony Relief Bank (SAB), Information to the losses on the residential and commercial building sector due to 2002 flood, submitted in December 2012.

[13] Maiwald, H. & Schwarz, J., Berücksichtigung der Fließgeschwindigkeit bei Hochwasser-Schadensmodellen. *Bautechnik*, **86**(9), pp. 550–565, 2009.

[14] Ministry of Land, Infrastructure and Transportation, Survey of tsunami damage condition. http://www.mlit.go.jp/toshi/toshi-hukkou-arkaibu.html. Accessed on: 2 Feb. 2022.

[15] Suppasri, A., Mas, E., Charvet, I., Gunasekera, R., Imai, K., Fukutani, Y., Abe, Y. & Imamura, F., Building damage characteristics based on surveyed data and fragility curves of the 2011 Great East Japan Tsunami. *Natural Hazards*, **66**(2), pp. 319–341, 2013.

[16] Suppasri, A., Charvet, I., Imai, K. & Imamura, F., Fragility curves based on data from the 2011 Tohoku-Oki Tsunami in Ishinomaki City, with discussion of parameters influencing building damage. *Earthquake Spectra*, **31**(2), pp. 841–868, 2015.

[17] Grünthal, G., Musson, R., Schwarz, J. & Stucchi, M., European macroseismic scale 1998. *Cahiers du Centre Européen de Geodynamique et de Seismologie*, ed. G. Grünthal, **15**, Luxembourg, 1998.

[18] Maiwald, H. & Schwarz, J., Unified damage description and risk assessment of buildings under extreme natural hazards. *European Journal of Masonry*, **23**(2), pp. 95–111, 2019.

[19] Maiwald, H. & Schwarz, J., Vulnerability assessment of multi hazard exposed building types: Development of an EMS-98 based empirical-statistical methodology. *16th World Conference on Earthquake Engineering,* Santiago, Chile, Paper No. 2134, 2017.

[20] Schwarz, J., Maiwald, H., Kaufmann, Ch., Langhammer, T. & Beinersdorf, S., Conceptual basics and tools to assess the multi hazard vulnerability of existing buildings. *European Journal of Masonry*, **23**(4), pp. 246–264, 2019.

[21] Kreibich, H., Piroth, K., Seifert, I., Maiwald, H., Kunert, U., Schwarz, J., Merz, B. & Thieken, A., Is flow velocity a significant parameter in flood damage modelling? *Natural Hazards and Earth System Sciences*, **9**(5), pp. 1679–1692, 2009.

[22] Bhola, P.K., Leandro, J., Konnerth, I., Amin, K. & Disse, M., Dynamic flood inundation forecast for the city of Kulmbach using offline two-dimensional hydrodynamic models. *13th International Conference on Hydroinformatic*, Palermo, Italy, 2018.

[23] Schwarz, J. & Maiwald, H., Berücksichtigung struktureller Schäden unter Hochwassereinwirkung. *Bautechnik*, **84**(7), pp. 450–464, 2007.

[24] Maiwald, H., Schwarz, J., Abrahamczyk, L. & Lobos, D., Das Magnitude 8.8 Maule (Chile)-Erdbeben vom 27. Februar 2010 – Ingenieuranalyse der Tsunamischäden. *Bautechnik*, **87**(10), pp. 614–622, 2010.

[25] Schwarz, J., Maiwald, H., Kaufmann, C. & Beinersdorf, S., Evaluation of the vulnerability of existing building stocks under single and multi-hazard impact. *16th European Conference on Earthquake Engineering (ECEE)*, Thessaloniki, Greece, 18–21 Jun., Paper 11641, 2018.

[26] Strangefield, P. & Stopp, H., Floating houses: An adaptation strategy for flood preparedness in times of global change. *Flood Recovery, Innovation and Response IV*, 2014.

[27] Maiwald, H. & Schwarz, J., Schadensmodelle für extreme Hochwasser – Teil 1: Modell-bildung und Validierung am Hochwasser 2002. *Bautechnik,* **91**(3), pp. 200–210, 2014.

[28] Schwarz, J., Maiwald, H. & Kaufmann, C., Unsicherheiten bei der Quantifizierung von Hochwasser-Schadenspotenzialen. *Bautechnik*, **93(**4), pp. 214–229, 2016.

[29] Suppasri, A., Imai, K., Imamura, F. & Koshimura, S., Comparison of casualty and building damage between Sanriku Ria Coast and Sendai Plain Coast based on the 2011 Great East Japan Tsunami. *International Sessions in Conference of Coastal Engineering, JSCE*, **3**, pp. 76–80, 2012.

[30] Foytong, P., Ruangrassamee, A., Shoji, G., Hiraki, Y. & Ezura, Y., Analysis of tsunami flow velocities during the March 2011 Tohoku, Japan, Tsunami. *Earthquake Spectra*, **29**(1), pp. 161–181, 2013.

[31] Hazus®-MH MR5, Earthquake loss estimation methodology, Advanced Engineering Building Module (AEBM), Technical and User's Manual, Federal Emergency Management Agency. https://www.hsdl.org/?view&did=12760. Accessed on: 5 Mar. 2022.

[32] Hochwasser in Rheinland-Pfalz und Nordrheinwestfalen 2021, Earthquake Damage Analysis Center, Weimar. https://edac.biz/forschung/hochwasser/feldeinsaetze/hochwasser-rheinland-pfalz-und-nordrheinwestfalen-2021. Accessed on: 21 Mar. 2022.