A new model for consideration of flow velocity in flood damage and loss prognosis

Holger Maiwald^{1,a}, Christian Kaufmann¹, Tobias Langhammer¹ and Jochen Schwarz¹

¹ Earthquake Damage Analysis Center, Bauhaus-Universität Weimar, Marienstrasse 13B, 99423 Weimar, Germany

Abstract. Reliable prognoses of building damage caused by flood impact require realistic relationships between action and damage or loss describing parameters. A remarkable progress is reached with the EDAC flood damage model which takes into account the vulnerability of the different building types and allows the prediction of structural damage as a function of flow velocity and inundation level over the specific energy height.

The paper discusses an extended method for the prognosis of structural damages and provides refined correlations between inundation level, moderate to high flow velocities in dependence of the vulnerability of the different building types and the number of stories of the building.

For lower flow velocities, typical for river floods, the study is based on a comprehensive qualified damage dataset collected after the flood 2002 in Saxony. Due to the lack of reliable damage data caused by high flow velocities in flash flood events, an innovative approach is adopted to extend the damage database by including and reevaluating the damage data from the tsunami after the 2011 Tohoku earthquake in Japan.

The developed tools are applied to the re-interpretation of the August 2002 flood damage. The calculated damage grades are transferred into loss statements. Results of the approach are presented for different study areas in the Free State of Saxony.

1 Motivation

The extreme flood events of recent years in Germany (2002, 2010, 2013) show that even extreme events with very low probabilities of occurrence are possible and can result in devastating damage. Especially the flood 2002 has shown that in addition to pure penetration damage more or less severe structural damage to the building substance might occur. Conventional flood loss models cannot consider this type of damage in an adequate way. An overview of such models could be found in Jongman *et al.* (2012).

Structural damage has mostly been examined in the past in terms of a collapse of the structure depending on the influence of the flow velocity in connection with the water level (Black, 1975, Sangrey *et al.*, 1975 and Smith, 1991) or additional criteria for a partial failure determined (Claussen and Clark, 1990). A refined differentiation to take into account the different damage patterns of structural damage, the conversion into concrete losses and the consideration of the spread in the damage with comparable effects are missing in these studies.

The vulnerability functions in the EDAC flood damage model (Maiwald and Schwarz, 2011) provide a first attempt to predict the structural damage in the form of damage grades depending on the building types, water level and specific energy height. Other parameters

influencing the vulnerability of the building are considered. The particularities of flash flood events (cf. Maiwald and Schwarz, 2016) have also not yet been adequately investigated. The previously available approaches for damage prognosis are not sufficient for higher flow velocities and strongly varying water levels that occur by such events.

Within the framework of 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), improved approaches are developed to take into account new combinations of water level and flow velocity and the vulnerability of the structure (building types, number of stories ...). The examined new damage prognosis tools will be presented in the paper and applied to different investigation areas in Saxony on a microscale level for the 2002 flood.

In the outlook of INNOVARU, the link to newly derived synthetic damage functions is given, while covering the entire range of a residential building stock in a more differentiated way.

Here, in a first step, the calculated structural damages are transferred into concrete loss statements with the already existing damage (loss) functions of the EDAC flood damage model (Maiwald and Schwarz, 2014a) and compared with the real observed losses.

^a Corresponding author: holger.maiwald@uni-weimar.de
DOI 10.3311/FLOODRisk2020.11.9

2 Database

2.1 Damage data

EDAC flood damage database

The EDAC flood damage database is the outcome of a comprehensive evaluation of damage reports of the Saxonian Relief Bank (SAB) for scientific purposes by order of the Dam Authority of the Free State of Saxony ("Landestalsperrenverwaltung Sachsen" - LTV).

The background was the development of reliable damage functions for residential buildings in support of benefit-cost evaluation of planned flood protection measures in the Free State of Saxony in Germany.

Damage reports were sighted and analysed for nearly all districts in Saxony affected by the 2002 flood. In addition to the relevant building parameters and the inundation levels, the descriptions of the structural damage and the actual recovery costs were evaluated.

The damage database contains approx. 5000 damage cases.

On the basis of hydraulic calculations, in Maiwald and Schwarz (2009) the flow velocities were approximately assigned to the individual damage cases ($n \approx 1000$) in four selected investigation areas in Saxony.

The data in the EDAC flood damage database, for which flow velocities can be assigned, generally relate to damage cases with moderate flow velocities typical of river floods. Flow velocities of about $v_{\max} \approx 2.5$ m/s could be assigned to the damage cases.

Reliable data for damage events due to higher flow velocities (such as by flash flood events) or the values of the flow velocities for such damage cases contained in the database are currently not available. For this reason, an innovative approach is chosen in which the damage database is expanded to include damage data resulting from the tsunami after the Tohoku earthquake in Japan in 2011.

Tsunami damage data

A comprehensive damage database ($n \approx 252,000$) is available for the tsunami after the 2011 "Tohoku earthquake" in Japan (MLIT). Based on this database, "Fragility Functions" are derived in Suppasri *et al.* (2013, 2015) for different building types 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 (Grünthal *et al.*, 1998) for earthquake shaking effects. An additional damage grade D6 was assigned to buildings that were completely washed away or completely overturned (see Suppasri *et al.*, 2015). Buildings that were not affected by the tsunami are excluded from the evaluations. Therefore, the lowest damage class has to be addressed at damage grade D1 (see also Schwarz and Maiwald, 2007).

The damage classification proposed by Suppasri *et al.* (2013, 2015) was taken into account by Maiwald and Schwarz (2019) to derive unified damage scales for the main natural hazard types.

The database was re-evaluated by Maiwald and Schwarz (2017) 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 MLIT database.

The flow velocities of the tsunami at selected points were estimated in Foyton *et al.* (2013) and Suppasri *et al.* (2012) using video recordings. Suppasri *et al.* (2012) also highlighted the differences between "plain coast" and "ria coast". The estimated flow velocities of these studies allow the derivation of average values of the Froude number according to the coastal classification in order to approximate flow velocities for the reconstructed damage data (see Maiwald and Schwarz, 2017).

2.2 Investigation areas

Table 1 gives an overview about the flood affected areas considered in this paper. Their geographical location can be taken from Figure 1.

The EDAC flood damage model was validated on the damage caused by the flood in 2002 in the four Saxonian towns of Döbeln, Eilenburg, Grimma and Flöha (cf. Maiwald and Schwarz, 2009, 2011, 2014a, b, 2015). One of the objectives was to select areas that differ in their flooding characteristics (inundation level and flow velocities).

In the study areas, the entire building stock affected by the 2002 flood was systematically investigated on site; the relevant building parameters (cf. Schwarz *et al.*, 2019) and the existing flood marks were documented.

For the INNOVARU project, the towns Pirna, Grimma and Freital in Saxony were selected as investigation areas.

Pirna was also systematically analyzed in a former study by one of the other project partner as test area for the application of synthetic damage functions (Naumann and Rubin, 2008; Naumann *et al.*, 2009). It should be noted that the affected buildings on the north-eastern bank of the Elbe remain unobserved.

The building stock of the city of Freital was documented on a microscale level using a coordinated parameter list which was implemented in an improved version of the "EQUIP" building survey tool developed at EDAC (cf. Schwarz *et al.*, 2018). The INNOVARU test area Freital is mentioned for completeness, but the hydraulic calculations for the 2002 flood in Freital are currently pending. The results of the investigations are therefore not yet included in the current state of studies.

Figure 1. Investigation areas in Free State of Saxony.

Investigation area	Building inspected (affected ¹)		Damage cases: SAB ² (EDAC) ³	Year of survey
	Residential	Total		
Pirna	1209 (950)	1405	1148 (366)	2008
Grimma	773 (690)	1280 (1186)	616 (306)	2009, 2017
Freital	1048	2096	865 (277)	2019
Eilenburg	1041 (1028)	2184 (2149)	961 (551)	2003, 2004
Döbeln	832 (788)	1429 (1348)	681 (276)	2004
Flöha	734 (721)	1872 (1828)	582 (154)	2009

Table 1. Overview of the investigation areas.

¹) acc. to flood scenarios (see 3.3)

²) reported to Saxonian Relief Bank (SAB, 2012)

³) included in EDAC flood damage data base

2.3 Flood scenarios

The improved methods in the paper will be validated on the 2002 flood in the investigation areas.

Inundations levels and flow velocities at the damaged buildings can be assigned (and only approximately) through a subsequent simulation of the flood event. Table 2 gives an overview of the applied 2D-scenarios. It is to differentiate between scenarios, which considers the building stock in detail or only over a mean roughness.

For the investigation area Grimma and Flöha 2D hydraulic calculations are available from the RIMAX project MEDIS (cf. Kreibich *et al.*, 2009). Figure 2 shows the spatial distribution of inundation levels and flow velocities in Grimma. Both models were provided by the Dam Authority of the Free State of Saxony.

Flow velocities for Eilenburg and Döbeln were derived within the MEDIS project (Kreibich *et al.*, 2009). For the investigations in Maiwald and Schwarz (2009), the Dam Authority of Saxony provided a hydraulic model with a higher resolution for Döbeln (PSL, 2009).

For the 2002 flood in Pirna is only a calculation for the “Elbe” flood available (Dam Authority Saxony). In order to take into account also the previous flooding from the tributaries “Gottleuba” and “Seidewitz” in the scenario, the scenario HQ 100 (which shows a good match with the official inundation areas) was approximated.

The subsequent hydraulic calculations for the 2002 flood are associated with larger uncertainties, since the hydrological boundary conditions have changed during this flood due to the strong erosion and rearrangement processes. Therefore, in Eilenburg, Döbeln and Flöha the water level model is also derived from documented flood marks in a simplified manner (cf. Maiwald, 2007).

From the approximated water surface level, the corresponding flood level for each individual building is derived using a Digital Elevation Model (DEM) with a resolution of 2 m by 2 m (Maiwald and Schwarz, 2014a).

Investigation area	Model approach	Grid size [m] ¹	Max. Water level h_{gl} [m] ²	Flow velocity v_n [m/s] ²
Pirna	2D (detailed)	variabel	0 - 4.1	0 - 3.1
Grimma	2D (detailed)	5 x 5 (h_{gl}) 1 x 1 (v_n)	0 - 5.0	0 - 2.7
Freital	currently under preparation			
Eilenburg	2D (mean roughness)	25 x 25	0 - 3.5	0 - 1.9
Döbeln	2D (detailed)	variabel	0 - 4.7	0 - 2.4
Flöha	2D (mean roughness)	5 x 5	0 - 2.8	0 - 2.3

Table 2. Overview of the flood scenarios for 2002 flood.

¹) for calculation

²) at building location

In an internal evaluation, these results showed better correspondence with the documented flood marks than the results from the hydraulic calculations. However, the flow velocities have to be taken from hydraulic calculations.

Figure 2. Inundation levels and flow velocities in Grimma for 2002 flood scenario.

3 Existing EDAC – flood damage model

3.1 Damage scale for flooding

Based on the building stock and documented damage to buildings recorded in August 2002, an initially five-stage differentiation of damage grades could be implemented in Schwarz and Maiwald (2007); it provides one of the basic elements in the flood damage model elaborated by the Earthquake Damage Analysis Center EDAC (Maiwald and Schwarz, 2011).

Some damage patterns that have seldom been observed in Germany (although indeed possible) however are still not considered. This currently applies to values from experience of serious flash floods (Maiwald and Schwarz, 2016), in which buildings (like in serious tsunamis) tip over, are displaced from their foundations or can be completely washed away.

Considering the experiences from the March 2011 tsunami in Japan (Suppasri *et al.*, 2013) and the tsunami damage analysed by the authors after the 2010 Maule earthquake in Chile (Maiwald *et al.*, 2010), a damage grade D6 (cf. Table 3) is introduced in Maiwald and Schwarz (2019) in order to delineate these extreme cases of damage from the grade for common collapse (D5).

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 <i>replacement of finshings necessary</i> <i>contamination</i>
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 <i>replacement of loadbearing walls, slabs</i>
D5	very heavy	very heavy	collapse of larger parts of building
D6	very heavy	very heavy	dislocation: building completely washed away, toppled or displaced from foundation

Table 3. Extended flood damage scale.

3.2 Flood vulnerability classes

The concept of vulnerability classes was developed for the earthquake intensity and observed shaking effects in the European Macroseismic Scale 1998 – EMS 98 (Grünthal *et al.*, 1998). This concept was successfully transferred to flood severity and damage interpretation in Maiwald and Schwarz (2007).

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 the comparable vulnerability in classes.

Vulnerability classes are an indicator of the behaviour under the effects of the impact or the resistance against it. Vulnerability class HW-A is representative for the most vulnerable buildings with the largest expected damages; the buildings of vulnerability class HW-F (newly introduced in Schwarz *et al.*, 2018) should survive strong impact level without significant damage. Vulnerability class HW-F (flood evasive design) is related to flood resistant constructions like floating homes.

There is a scatter of possible vulnerability classes for each building type:

- most likely vulnerability class
- probable range
- range of less, probable, exceptional cases.

The most likely class and the range of scatter follow from a variety of damage assessments; they are expressed by characteristic symbols, which are adopted unchanged in the flood-vulnerability table (cf. Table 4). The ranges of scatter may be different in both directions (lower or higher vulnerability), or even tend to spread only in one direction. The specific classification within the range of scatter depends on the condition and the structural design of the building.

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

Table 4. Classification of building types in vulnerability classes and identification of ranges of scatter.

3.3 Specific Vulnerability Functions (SVF) – prognosis of structural damage

The EDAC flood damage model (Maiwald and Schwarz, 2009, 2011, 2015) takes into account the vulnerability of the different building types and allows the prediction of structural damage as a function of flow velocity v_{fl} and inundation level above ground level h_{gl} in form of the specific energy height H (see Eq. (1)).

The Specific Vulnerability Functions SVF Type 2b in Eqs. (2) and (3) acc. to the EDAC flood damage model (cf. Maiwald and Schwarz, 2011) were derived from around 1000 damage cases of the EDAC flood damage database for which flow velocities were available from hydraulic calculations.

$$H = h_{gl} + \frac{v_{fl}^2}{2g} \quad (1)$$

The functions, shown in Figure 3, are classified according to the flood vulnerability classes (Maiwald and Schwarz, 2009). The model assumes a hyperbolic tangent function as mathematical background to calculate the mean damage grade D_m according to Eq. (2) and (3) and is defined for the mean damage grades D_m in the original interval 1 to 5 (D1 to D5).

$$D_m = 2 \cdot \tanh\left(f(h_{gl}, v_{fl})\right) + 3 \quad (2)$$

$$D_m = 2 \cdot \tanh\left(A \cdot (H - 2) + B\right) + 3 \quad (3)$$

Figure 3. Specific Vulnerability Functions of type $D_m = f(h_{gl}, v_{fl})$.

3.4 Specific Damage Functions (SDF) – loss prediction

Following the proposed methodology, a set of Specific Damage Functions (SDF) for loss predictions were presented in Maiwald (2007) and Maiwald and Schwarz (2009, 2011, 2014a, 2015). Functions refer to the building type (SDF Type 1a) or flood vulnerability class (SDF Type 1b). A second type of functions (SDF Type 2), which are used in this paper, transfer the calculated damage grades D_i into relative loss statements.

All of the developed functions consider the number of stories and the presence of a cellar (Schwarz and Maiwald,

2007). The mathematical background of the different types of damage functions is based on an exponential approach (Eq. 4) and is outlined in Maiwald (2007) and in Maiwald and Schwarz (2011, 2015).

Figure 4 shows the examples for damage grades D2 and D4 for buildings with basement (cf. Maiwald and Schwarz, 2014a). The derived functions include values above 100% taking into account the demolition and disposal costs (cf. Maiwald and Schwarz, 2011).

$$L(h_{gf}) = A \cdot e^{B \cdot h_{gf}} \quad (4)$$

The functions can be applied to calculate the losses to the building structure (including building services) in dependence of the inundation level over the ground floor level (h_{gf}). The main application is the general residential building stock. An application for other types of use should also be possible for similar building construction.

Both types of functions indicate the loss (L) as a relative fraction of the replacement value, which can be calculated for a building in Germany using the so called Normal Construction Costs (Normalherstellungskosten - NHK 2000) together with the building price index of the Federal Statistical Office (Statistisches Bundesamt, 2020) for the corresponding reference year.

Further details for the application can be taken from Maiwald and Schwarz (2011, 2015).

a) Damage grade D2

b) Damage grade D4

Figure 4. Examples of the Specific Damage Functions SDF Type 2 provided for the different damage grades.

4 Improved prognosis of structural damages

4.1 Consideration of inundation level and flow velocity

Validations of the already existing model from section 3.3 and 3.4 showed good agreement with the damage actually observed (cf. Maiwald and Schwarz, 2009, 2011, 2014a, b, 2015).

Nevertheless, with respect to the mathematical formulation of the specific energy height H acc. to Eq. (1) it must be stated that the influence of the flow velocity is relative small.

Also, the recently introduced 6-stage unified damage scale in Maiwald and Schwarz (2019) requires a review and revision of the vulnerability functions.

The unification of the damage grade description (Maiwald and Schwarz, 2019) and the introduction of 6-stage vulnerability tables for flood and tsunami impact (Schwarz *et al.*, 2018) allow the combination of the two datasets from section 2.1 to a well-adjusted (updated) damage database, which can be analysed for the different vulnerability classes in dependence of the impact. In the study, only the tsunami damage cases up to 6 m inundation level are considered.

Figure 5 shows the combination of the datasets for vulnerability class HW-C on the basis of calculated mean damage grades D_m for clustered damage data for different height level and the corresponding flow velocities.

It should be noted that the tsunami damage data can be seen along a clearly defined area of impact, which can be justified by the approximate estimation of the flow velocities. Here, an extended analysis and the re-calculation of the flow velocities proposed by De Risi *et al.* (2017) could be a meaningful improvement.

Figure 5. Clustered damage data for vulnerability class HW-C.

Nevertheless, a reliable damage model can currently be derived, presuming a plausible mathematical model might be specified.

The basic approaches for the formulation of vulnerability functions to predict the structural damage using a tangent hyperbolic function remain in the paper following Eq. (5) and are considering now the interval between 1 and 6 (D1 to D6).

Five different variants acc. to Eq. (6) to (10) are investigated in this paper:

Variant V1 only transfers the existing approach from Maiwald and Schwarz (2009) to the 6-stage damage scale.

Variant V2 uses the flood intensity $I_{fl}=h_{gl} \times v_{fl}$ from the so-called Swiss model which represents a combination water level and flow velocity but without an extended physical background.

Variant V3 includes the water level h_{gl} and the momentum flux $h_{gl} \times v_{fl}^2$ (which is related to the hydrodynamic forces). The term is not unit loyal, but it considers that by low or not available flow velocities also the water level alone has an influence to the structural damage.

Variant V4 consider the momentum flux as physically based input parameter alone.

Variant V5 is similar to Variant 3, but weights the influence of the inundation level in a bit another way.

$$D_m = 2.5 \cdot \tanh\left(f\left(h_{gl}, v_{fl}\right)\right) + 3.5 \quad (5)$$

Variant V1: Specific energy height H

$$D_m = 2.5 \cdot \tanh\left(A \cdot H + B\right) + 3.5 \quad (6)$$

Variant V2: Water level h_{gl} + flood intensity $h_{gl} \times v_{fl}$

$$D_m = 2.5 \cdot \tanh\left(A \cdot h_{gl} + B \cdot h_{gl} \cdot v_{fl} + C\right) + 3.5 \quad (7)$$

Variant V3: Water level h_{gl} + momentum flux $h_{gl} \times v_{fl}^2$

$$D_m = 2.5 \cdot \tanh\left(A \cdot h_{gl} + B \cdot h_{gl} \cdot v_{fl}^2 + C\right) + 3.5 \quad (8)$$

Variant V4: Momentum flux $h_{gl} \times v_{fl}^2$

$$D_m = 2.5 \cdot \tanh\left(A \cdot h_{gl} \cdot v_{fl}^2 + B\right) + 3.5 \quad (9)$$

Variant V5: Water level h_{gl} + momentum flux $h_{gl} \times v_{fl}^2$

$$D_m = 2.5 \cdot \tanh\left(A \cdot \sqrt{h_{gl}} + B \cdot h_{gl} \cdot v_{fl}^2 + C\right) + 3.5 \quad (10)$$

A, B, C – Control (regression) parameter

The regression parameters are derived for the vulnerability classes HW-B to HW-D by a non-linear regression procedure. With respect to the lack of damage data for the flood vulnerability class HW-A, the control parameters were derived for this vulnerability class by an extrapolation procedure, which can be understand as an engineering approximation.

a) Variant V1

d) Variant V4

b) Variant V2

e) Variant V5

c) Variant V3

Legend (Damage Grade):

Figure 6. Vulnerability functions for flood vulnerability classes depending on inundation level and flow velocity.

An improvement of the model by applying sophisticated regression methods, which are mentioned in the literature (Charvet *et al.*, 2017, De Risi *et al.*, 2017), is to be discussed only at the academic level. Looking at the size of the uncertainties by the assignment of impact parameter, building types or other vulnerability related parameter to the damage data, it is unlikely to reach a model improvement at this point of the research and state of study.

The developed refined damage prognosis model allows the representation of the mathematical relationships in a 3D parameter surface.

Figure 6 displays that the mean damage grade D_m does not start at D1 even at 0m water level above ground level, but it is considered here that groundwater inundation can also cause structural damage.

Figure 6 already shows graphically that there are (practically) implausible relationships in some variants. Here the physically consistent variants prove to be problematic regarding their qualitative progression.

Variant V1 implies that at an inundation level $h_{gl}=0m$ and increasing flow velocities (which cannot occur here), higher structural damage results.

Variant V4 does not take into account the increase in structural damage with increasing water levels when the water movement is still ($v_{fl}=0$ m/s).

From the practical point of view, meaningful correlations are provided by variants 2, 3 and 5. Nevertheless, also the outcome of variants 1 and 4 will be further investigated.

4.2 Consideration of inundation level, flow velocity and the number of stories

The influence of the number of stories on the structural damage was already examined in Maiwald (2007) for masonry structures depending on the water level above the ground floor level h_{gl} using a smaller (limited) data set.

It could be shown that mean damage grades D_m decreases with increasing number of stories. This is due to the higher static requirements of multi-storey buildings.

In this study, the influence of the different number of stories should also be emphasized, taking into account the flow velocity. Since the data in the MLIT database are not broken down by number of stories, their influence is analyzed only on the basis of the damage data from the 2002 flood and transferred to the calculation models from section 4.1.

Therefore, in a first step simplified vulnerability functions were derived considering the vulnerability classes and the inundation level above the ground level. The trend in the clustered damage data is clearly visible in the example for HW-C in Figure 7. The outliers at higher inundation levels ($h_{gl} \geq 3.5m$) can be explained by the small number of damage cases in these clusters. The simplified vulnerability functions follow Eq. (11).

It has to be taken into account that primarily small numbers of stories lead to an increase of the structural damage. The influence is therefore weighted using the natural logarithm in the related term.

Figure 7. Damage data and simplified vulnerability functions for HW-C considering inundation level above ground level h_{gl} and number of stories.

The determined mathematical relationships were transferred and implemented in the vulnerability functions from 4.1.

This leads to Eqs. (12) to (16) for the extension of the variants V1 to V5. For Variant V3 as an example, the 3D surface diagrams for vulnerability classes HW-A to HW-D can be taken from the graphs in Figure 8.

$$D_m = 2.5 \cdot \tanh(A \cdot h_{gl} + B \cdot \ln(n_{st}) + C) + 3.5 \quad (11)$$

Variant V1: Specific energy height H

$$D_m = 2.5 \cdot \tanh(A \cdot H + B \cdot \ln(n_{st}) + C) + 3.5 \quad (12)$$

Variant V2: Water level h_{gl} + flood intensity $h_{gl} \times v_{fl}$

$$D_m = 2.5 \cdot \tanh(A \cdot h_{gl} + B \cdot h_{gl} \cdot v_{fl} + C \cdot \ln(n_{st}) + D) + 3.5 \quad (13)$$

Variant V3: Water level h_{gl} + momentum flux $h_{gl} \times v_{fl}^2$

$$D_m = 2.5 \cdot \tanh(A \cdot h_{gl} + B \cdot h_{gl} \cdot v_{fl}^2 + C \cdot \ln(n_{st}) + D) + 3.5 \quad (14)$$

Variant V4: Momentum flux $h_{gl} \times v_{fl}^2$

$$D_m = 2.5 \cdot \tanh[A \cdot h_{gl} \cdot v_{fl}^2 + B \cdot \ln(n_{st}) + C] + 3.5 \quad (15)$$

Variant V5: Water level h_{gl} + momentum flux $h_{gl} \times v_{fl}^2$

$$D_m = 2.5 \cdot \tanh(A \cdot \sqrt{h_{gl}} + B \cdot h_{gl} \cdot v_{fl}^2 + C \cdot \ln(n_{st}) + D) + 3.5 \quad (16)$$

A, B, C, D – Control (regression) parameters

a) HW-A

d) HW-D

Legend (Damage Grade):

Figure 8. Vulnerability functions (Variant V3) depending on inundation level, flow velocity and number of stories.

b) HW-B

c) HW-C

5 Validation of the improved model

The innovative options and advantages of the whole procedure are demonstrated by case studies from the 2002 flood in Saxony. With the developed new variants of the vulnerability functions in section 4.2, the mean damage grade D_m can be calculated for each individual building (microscale level) in the study areas and towns of Saxony (Figure 1).

The predicted mean damage grades D_m were transferred into loss statements with the Specific Damage Functions SDF Type 2b (see section 3.4).

On the one hand, an exact address based cartographic representation is problematic for different reasons and can lead to uncertainty among the homeowners, an anonymous representation of the damage grades and the losses in a mesoscale level is preferable. On the other hand, a comparison of the predicted damage with the real observed one only makes sense for a larger number of buildings.

As a remarkable progress to this aspects, Figures 9 and 10 show for the study areas the comparison of the calculated and the observed mean damage grades MD_m in the land use areas according to the “Amtliches Topographisch-Kartographisches Informationssystem” - (ATKIS) for Germany, which are composed by the mean damage grades D_m for the individual buildings.

Figure 9: Calculated mean damage grades MD_m in the ATKIS land use areas (micro-scale damage calculation).

Figure 10: Observed mean damage grades MD_m in the ATKIS land use areas (based on single damage cases, 2002 flood).

Legend for Figure 9 and 10:

The calculated mean damage grades MD_m for the variants V3 and V5 deviate only slightly from the observed damage grades (mostly $\Delta MD_m < 0.5$). The existing differences can be explained by the relatively small number of documented damage cases in some of the land use units.

The predicted losses of the already existing and the improved method are compared with the with the final official damage statistics of the Saxonian Relief Bank (SAB 2012) in Figure 11. It should be noted, not all of the really damaged residential buildings were included in the compensation program of the SAB (cf. Table 1).

Therefore, a scaling of the reported losses (“reported 2012”) to the existing number of residential buildings was necessary (“scaled 2012”). The comparison shows a good agreement for the residential building stock (Figure 11a). This is true for all of the calculated variants despite the different flooding characteristics in the study areas.

The overestimation of the total losses in Eilenburg and Flöha visible in Fig. 11b is due to the application of the damage functions to large-scale industrial building complexes, which still existed during the 2002 flood. For these uses, other damage functions have to be applied or complex individual case studies have to be carried out.

Refined loss prognosis tools in form of synthetic damage functions are currently under preparation (Golz *et al.*, 2020.) as part of the INNOVARU project, which will allow a differentiated loss prognosis in the future.

Figure 11. Comparison of calculated and reported losses in the investigation areas for the 2002 flood

6 Conclusions and outlook

Considering the elements of the existing EDAC flood damage model, new mathematical formulations for the prognosis of the structural damages due to flood impact are developed in the paper. The refined model provides basic tools for the prediction of structural damage of the building taking into account the specific building vulnerability, the inundation level and the flow velocity.

The derived new vulnerability functions enable in principle also damage prognosis for events with high flow velocities.

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 different study areas with moderate flow velocities. In all cases, a remarkably good agreement between the predicted and the reported losses can be stated for inventory of residential buildings.

The model has to be validated at events with high flow velocities, which can be expected by flash floods. The damage caused in Braunsbach (Germany) 2016 might serve as a reference event (Maiwald and Schwarz, 2016).

So-called “fragility functions” are currently being derived, with which the exceedance probability of a certain damage grade can be quantified depending on inundation level and flow velocity. This type of functions allows the identification and implementation of the scatter of structural damage. It also enables a simulative damage prognosis using the Monte Carlo method, which can then provide the basis for loss calculations and to quantify the scatter within the financial loss indicators.

An improvement in the loss prognosis can be expected by the application of new synthetic damage functions that take into account the concept of the damage grades.

Acknowledgements

Significant parts of the methodological approaches presented were developed as part of the joint research project funded by the German Federal Ministry of Education and Research (BMBF):

Innovative Vulnerabilitäts- und Risikobewertung urbaner Räume gegenüber Überflutungsereignissen – INNOVARU (Innovative Vulnerability and Risk Assessment of Urban Areas against Flood Events).

Information:

https://www.sifo.de/files/Projektumriss_INNOVARU.pdf

7 References

1. Black, R. D. (1975). *Floodproofing Rural Residences*. Washington D.C. Report no EDA 77-088. US Department of Commerce, Economic Development Administration.
2. Bundesministerium für Verkehr, Bau- und Wohnungswesen. Normalherstellungskosten 2000 (NHK 2000). https://www.bundesanzeiger-verlag.de/fileadmin/BIV-Portal/pdf/NHK_2000.pdf, 7.02.2020.
3. Charvet, I., Macabuag, J. and Rossetto, T. (2017). Estimating Tsunami-Induced Building Damage through Fragility Functions: Critical Review and Research Needs. *Frontiers in Built Environment* Vol. 3: Article 36.
4. Clausen, L. and Clark, P. B. (1990). 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.
5. De Risi, R., Goda, K., Yasuda, T. and Mori N. (2017). Is flow velocity important in tsunami empirical fragility modeling? *Earth-Science Reviews* 166(3):64-82.
6. Foytong, P., Ruangrassamee, A., Shoji, G., Hiraki, Y. and Ezura, Y. (2013). Analysis of tsunami flow velocities during the March 2011 Tohoku, Japan, Tsunami. *Earthquake Spectra*, 29(1): 161-181.
7. Golz, S., Wehner, T. and Naumann, T. (2020). Quantifying flood resilience of buildings: a synthetic approach for risk mitigation. *Journal of flood risk management* (forthcoming).
8. Grünthal, G. (ed.), Musson, R., Schwarz, J. and Stucchi, M. (1998): European Macroseismic Scale 1998. *Cahiers du Centre Européen de Géodynamique et de Séismologie*, Volume 15, Luxembourg.
9. Jongman, B., Kreibich, H., Apel, H., Barredo, J.I., Bates, P.D., Feyen, L., and Gericke, A. Neal, J., Aerts, J. C. J. H., and Ward P. J. (2012). Comparative flood damage model assessment: towards a European approach. *Natural Hazards and Earth System Sciences (NHESS)* 12(12): 3733-3752.

10. Kreibich, H., Piroth, K., Seifert, I., Maiwald, H., Kunert, U., Schwarz, J., Merz, B. and Thieken, A. (2009). Is flow velocity a significant parameter in flood damage modelling? *Natural Hazards and Earth System Sciences (NHESS)* **9**(5): 1679-1692
11. Maiwald, H. (2007). *Ingenieurmäßige Ermittlung von Hochwasserschadenspotentialen im mikroskaligen Maßstab*. Dissertation, Fakultät Bauingenieurwesen der Bauhaus-Universität Weimar.
12. Maiwald, H. and Schwarz, J. (2009): Berücksichtigung der Fließgeschwindigkeit bei Hochwasser-Schadensmodellen. *Bautechnik* **86**(9): 550-565.
13. Maiwald, H., Schwarz, J., Abrahamczyk, L. and Lobos, D. (2010): Das Magnitude 8.8 Maule (Chile)-Erdbeben vom 27. Februar 2010 – Ingenieuranalyse der Tsunamischäden. *Bautechnik* **87**(10): 614–622.
14. Maiwald, H. and Schwarz, J. (2011). *Ermittlung von Hochwasserschäden unter Berücksichtigung der Bauwerksverletzbarkeit, EDAC-Hochwasserschadensmodell*. Scientific Technical Reports 01-11, Zentrum für die Ingenieuranalyse von Erdbebenschäden, Universitätsverlag, Bauhaus-Universität Weimar.
15. Maiwald, H. and Schwarz, J. (2014a). Schadensmodelle für extreme Hochwasser – Teil 1: Modellbildung und Validierung am Hochwasser 2002. *Bautechnik* **91**(3): 200-210.
16. Maiwald, H. and Schwarz, J. (2014b): Neue Schadensmodelle zur Bewertung der Konsequenzen von extremen Hochwassern, *Informationstag Ingenieurbau. Innovation, Normung, Praxis*. Institut für Konstruktiven Ingenieurbau der Bauhaus-Universität Weimar in Zusammenarbeit mit der Bauhaus Akademie Schloss Ettersburg.
17. Maiwald, H., Schwarz, J. (2015). Damage and Loss Prognosis Tools Correlating Flood Action and Building's Resistance-type Parameters. *International Journal of Safety and Security Engineering* **5**(3): 222-250.
18. Maiwald, H. and Schwarz, J. (2016). Die Sturzflut von Braunsbach - Ingenieuranalyse der Gebäudeschäden. *Bautechnik* **93**(12): 925-932.
19. Maiwald, H. and Schwarz, J. (2017). Vulnerability assessment of Multi Hazard exposed building types - development of an EMS-98 based empirical-statistical methodology. *Proceedings 16th World Conference on Earthquake Engineering*, Santiago, Chile, 2017, Paper No. 2134.
20. Maiwald, H. and Schwarz, J. (2019). Unified damage description and risk assessment of buildings under extreme natural hazards. *Europaen Journal of Masonry* **23**(2): 95-111.
21. Maiwald, H., Schwarz, J., Abrahamczyk, L. and Lobos, D. (2010). Das Magnitude 8.8 Maule (Chile)-Erdbeben vom 27. Februar 2010 – Ingenieuranalyse der Tsunamischäden. *Bautechnik* **87**(10): 614–622.
22. Ministry of Land, Infrastructure and transportation (MLIT). Survey of tsunami damage condition: <http://www.mlit.go.jp/toshi/toshi-hukkou-arkaibu.html>, 28.01.2020.
23. Naumann T. and Rubin, C. (2008). Ermittlung potenzieller Hochwasserschäden in Pirna nach dem gebäudetypologischen VERIS Elbe-Ansatz. In: *Tagungsband zum DWA-Seminar Hochwasserschadensinformationen: Neues und Bewährtes*. Hennef: 86–101.
24. Naumann, T., Golz, S. and Nikolowski, J. (2009). Synthetic depth-damage functions—a detailed tool for analyzing flood resilience of building types. *Proceedings Final Conference of the COST action C22 Urban Flood Management in cooperation with UNESCO-IHP*, Paris.
25. PSL (2009). Ergebnisse der 2D-HN-Modellierung Döbeln für den Ist-Zustand 8/2002, Wassertiefen- und Geschwindigkeitsskizzen, GRIDS und -TINS. Planungsgesellschaft Scholz und Lewis mbH: Landestalsperrenverwaltung Sachsen.
26. Sächsische Aufbaubank / Saxony Relief Bank – SAB (2012). Information to the losses on the residential and commercial building sector due to 2002 flood in Saxony, Excel table, submitted in 12/2012.
27. Sangrey, D. A., Murphy, P. J. and Nieber, J. L. (1975). *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.
28. Schwarz, J. and Maiwald, H. (2007). Berücksichtigung struktureller Schäden unter Hochwassereinwirkung. *Bautechnik* **84**(7): 450–464.
29. Schwarz, J. and Maiwald, H., Kaufmann, C. and Beinersdorf, S. (2018): 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 June 2018.
30. Schwarz, J., Maiwald, H., Kaufmann, Ch., Langhammer, T. and Beinersdorf, S. (2019). Conceptual basics and tools to assess the multi hazard vulnerability of existing buildings. *Europaen Journal of Masonry* **23**(4): 246-264.
31. Smith, D. I. (1991). Extreme floods and dam failure inundation implications for loss assessment. *Proceedings of a Seminar "Natural and Technological Hazards: Implications for the Insurance Industry"*: 149-165.
32. Statistisches Bundesamt (2020). *Preisindizes für die Bauwirtschaft*. Fachserie 17, Reihe 4.
33. Suppasri, A., Imai, K., Imamura, F. and Koshimura, S. (2012): Comparison of casualty and building damage between Sanriku Ria Coast and Sendai Plain Coast based on the 2011 Great East Japan Tsunami, *Proceedings of International Sessions in Conference of Coastal Engineering, JSCE, Vol. 3*: 76-80.
34. Suppasri, A.; Mas, E.; Charvet, I.; Gunasekera, R.; Imai, K.; Fukutani, Y.; Abe, Y. and Imamura, F. (2013). Building damage characteristics based on surveyed data and fragility curves of the 2011 Great East Japan Tsunami. *Natural Hazards* **66**(2): 319-341.
35. Suppasri, A., Charvet, I., Imai, K. and Imamura, F. (2015). 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): 841-868.