

DAMAGE AND LOSS PREDICTION MODEL BASED ON THE VULNERABILITY OF BUILDING TYPES

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ABSTRACT: Reliable prognoses of building damage caused by flood impact require realistic relationships between action and damage or loss describing parameters. Due to the fact that commonly applied damage functions are related to the different usage classes (i.e. private housing), the required differentiation according to the parameters on the resistance side is still missing. The large scatter within the data and statistics of observed damage cases have complicated the derivation of reliable loss predictions and cost-benefit analyses. On the basis of the August 2002 Saxony flood data base, a method to determine the structural damage of a single building (micro-scale) or of the affected building stock (meso- and macroscale) for any given flood scenario is developed. Repeatedly observed damage patterns are transformed into a classification scheme of damage grades. With this tool, the structural damage of all damage cases can be analyzed in a systematic way. The paper gives an overview of the basic steps of the procedure and different fields of application.

Key Words: structural damage, damage grades, vulnerability functions, loss model

1. INTRODUCTION

Estimating damage caused by flood impact is an important, yet scientifically and methodically insufficiently investigated task. The large scatter within the scarcely available damage data as well as the remarkable diversity (in shape and amplitude characteristics) of the statistically derived damage functions are contributing to uncertain and often misleading loss predictions. The situation is still more complicated as harmonized damage assessment procedures and documentation manuals are missing. Within the framework of comprehensive research projects an essential progress is reached in the understanding of the problems and the search for more interdisciplinary solution strategies.

The paper refers to the development of a damage and loss prediction model based on an engineering evaluation system of buildings subjected to different natural hazards (EDAC, 2008). Alluding to the procedure developed in the risk analysis of earthquakes, it is checked, whether methodical fundamentals can be transferred or have to be adopted, and which parameters must be derived from data surveys. As an essential improvement, in addition to the inundation level (flood action side), the impact of structural parameters (resistance side) is considered (Schwarz *et al.*, 2007). In this context, the detailed survey and the documentation of damage cases provide the basis to establish a new set of damage functions and to

validate the developed GIS-based risk assessment technologies by comparing the predicted with the observed building damage or loss quantities.

Preliminary results of the approach are concentrated on the case studies of the towns Eilenburg, Döbeln and Grimma, being particularly affected by the 2002 flood in Saxony (Eastern Germany). Innovative damage and loss assessment procedures are developed including the unified definition of global structural Damage Grades (D_i) and Specific Vulnerability Functions (SVF), Specific Damage Functions (SDF) being related to the damage and loss or the specific flood vulnerability classes (HW-VC) of a building or object. As is it can be shown, the tools enable the reinterpretation of damage with respect to structural and loss parameters, and are, therefore, suited for prognoses purposes and short- and long-term disaster management decisions.

2. DATA BASE

The key element of the procedure lies in the preparation of the real damage cases, which were elaborated immediately after the 2002 floods in Saxony. As a whole two different datasets are considered and combined within the frame of the RIMAX-MEDIS project:

- Dataset 1 (“EDAC”): Data are elaborated immediately by field surveys after the August 2002 flood and by distribution of questionnaires in 2003 and 2004 (Schwarz *et al.*, 2005); see also Figure 2a. Damage cases are related to the building stock in Saxony, alongside the river system of the Unified Mulde, Freiburger Mulde and Zschopau, being particularly affected; e.g. high damage grades are documented (cf. Table 1). Additionally, questionnaires are distributed in regions of Baden-Wuerttemberg while referring to series of events between 1978 and 1994.
- Dataset 2 (“MEDIS”): Data are gained (as part of the MEDIS-project) by a campaign of telephonic interviews with building owners after two moderate floods in Bavaria 2005 and in Saxony 2006 (here alongside the river Elbe).

After having unified the data with respect to the structural parameters and having transferred the verbal damage descriptions into the proposed scheme of damage grades, the datasets could be considered, separately and as combination (Dataset 1 + 2 :“EDAC+MEDIS”). The datasets include information about duration, velocity (qualitatively) and other secondary (probably damage contributing) flood action as well as vulnerability-related parameters. They are quite complementary with respect to parameter ranges of inherent data points, and are leading to a well distributed database. Nevertheless, due to the differences within, the derived damage functions have an impact on the prognosis results (see Figure 1).









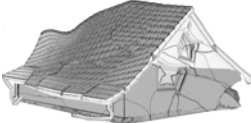

3. BASIC ELEMENTS OF THE FLOOD DAMAGE AND LOSS PREDICTION MODEL

During the last years, and as an outcome of practical request, several research projects of the Earthquake Damage Analysis Center (EDAC) are concentrated on the development of an engineering evaluation system of buildings subjected to natural hazard and the elaboration of more refined tools to link modular arranged elements of hazard, action, vulnerability, damage and loss in a modular way (cf. Schwarz *et al.*, 2005, EDAC, 2008). The procedures and the processing levels implemented in the model are structured transparently and can be used for different risk types (earthquake, storm, flood etc.). Basics steps of the procedure are derived from analogy considerations to the empirical, intensity-oriented method introduced for the earthquake damage and loss model on the basis of EMS-98 (Grünthal *et al.*, 1998). Mainly focusing the consideration on structural damage due to flood impact, characteristic vulnerability classes are determined for the different building types. Their vulnerability functions are derived by the following step-by-step explained procedure.

3.1 Harmonization of damage descriptions and assignment of repeatedly observed effects

Field surveys have to be qualified with respect to the documentation of damage cases and the collection of structural parameters affecting the vulnerability of each building. The documentation has to implement (as a minimum requirement) an “engineered” description of the building and its structural damage, and to archive typical damage pattern. Repeatedly observed effects are used as indicators for the definition of damage grades. In addition to the structural damage, observed damage-indicating phenomena can be related to chemical or physical origin (Schwarz *et al.*, 2007). For the damage classification, rehabilitation measures are of importance to convert the visible action or technological term into a generalized scheme of damage interpretation. Table 1 summarizes the main criteria for the classification of observed effects and damage reports, in an extended (widely applicable) format.

Table 1: Assignment of damage grades D_i to damage cases (Schwarz and Maiwald, 2007)

D_i	Damage		Description	Drawing	Example
	Structural	Non-structural			
D1	no	slight	only penetration and pollution		
D2	no to slight	moderate	slight cracks in supporting elements impressed doors and windows contamination replacement of extension elements		
D3	moderate	heavy	major cracks and / or deformations in supporting walls and slabs settlements replacement of non supporting elements		
D4	heavy	very heavy	structural collapse of supporting walls, slabs replacement of supporting elements		
D5	very heavy	very heavy	collapse of the building or of major parts of the building demolition of building required		

3.2 Definition of damage grades

Repeatedly observed effects can be regarded as typical building response indicators for a comparable level of damage, loss of integrity, stability etc. Table 1 provides the background for the necessary generalization of any damage classification. By the definition of damage grades (D_i), a unified evaluation of all damage data and reports seems to be guaranteed. Damage grades enabling the logic link between flood impact and loss in an innovative way. In all cases a minimum damage grade D1 (without the occurrence of structural damage) has to be assigned due to humidity penetration effects. The generalized damage definition is related to the quality of structural damage and non-structural damage as well as to the required extent of rehabilitation or other damage replacement measures (cf. Table 1).

3.3 Correlation between flood impact parameters and building damage (D_i)

In the majority of cases, the damage descriptions submitted by the questionnaires, telephone calls or other reports have to be translated into damage grades. This essential work has been performed by engineers from EDAC staff on the basis of the developed evaluation tools (Table 1). For each damage case the grade of damage D_i ($i = 1$ to 5) and the flood action parameters could be assigned. On the basis of a sample individual damage grades (i.e. for the same building type under comparable inundation heights) the mean damage grade (D_m) can be determined, being a robust parameter for damage prognosis in case of meso-scaled level of input (or intended output) parameters (see Figure 1). The level of ground floor is taken as reference height for the flood impact (h_{gr}). By this definition of inundation height, it is recognized that at this level an abrupt change of structural systems (cellar to ground floor) and, consequently, of vulnerability might occur. Therefore, in the vicinity of $h_{gr} = 0$, discontinuities in the vulnerability function curve indicate the new quality of the approach, i.e., vulnerability classes of cellar and other building floors have to be assigned, separately (see Figure 1).

For the all masonry buildings included in the datasets mean damage grades D_m are calculated for intervals of inundation height (Δh). Results of this procedure are illustrated for the predominant building type (masonry wall structures). Taking as interval of inundation height $\Delta h = 0.5$ m, the increase of mean damage grade (D_m) with the impact parameter becomes evident. The dots derived from both basic datasets of this study create the new type of damage functions.

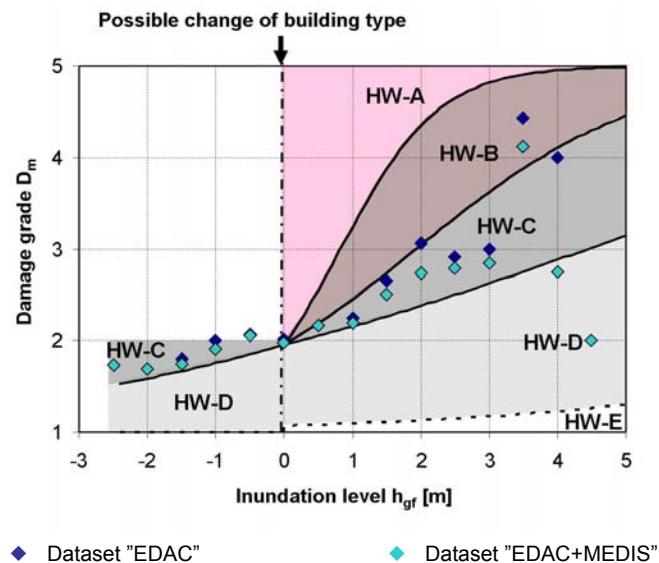


Figure 1: Damage grades, inundation level and vulnerability classes; results for masonry buildings

3.4 Ranges of vulnerability classes for the predominant building types

For each building the characteristic building type (or structural system) and its vulnerability class have to be identified. "Vulnerability" is taken as a measure for the resistance of a building against comparable impact conditions (inundation height, flow velocity) and is related to the differences in the damage (or loss) under these action parameters. Vulnerability functions are expressions of the existing correlations. Their quality can be improved by assigning the typical ranges and the scatter for the regionally predominant building types. Buildings of different structural type and material belong to the same vulnerability class, if for the relevant range of flood action parameter, similar mean damage grades have to be expected (Table 1). Due to the uniform quality of the database it was possible to identify typical shapes of (still idealized) vulnerability describing functions (see Figure 1).

As a whole, five Flood Vulnerability Classes (here: HW-A to HW-E) are distinguished by definition, covering the range from low flood resistance/higher vulnerability (A - very sensitive; B - sensitive), to normal (C) and increased flood resistance (D). Hypothetically, a flood resistant design (FRD) would lead to the class (HW-E). Class HW-E buildings (as recommended in common guidelines) are characterized by a separation of building from the flood water table, for instance, by "up-lifting" the base floor over a raster of story-high columns.

To convert each building of the dataset into its vulnerability class, a classification scheme is required taken into account the data density as well as the scatter within the representative (samples) of each building type (see Table 2). For each building the characteristic structural system (here denoted as building type) has to be identified. Subsequently, the building types have to be sorted into their appropriate vulnerability classes, whereas most likely, still probable and also exceptional cases have to be considered (Table 2). The symbols in Table 2 replace empirical vulnerability functions in a robust way. The lines (full, broken) indicate the range of scatter and the probability of occurrence. In case of an inundation height about $h_{gf} = 2.0$ m, a building of vulnerability class HW-C will suffer damage grade between D2 and D3, a building of vulnerability class HW-B sustain the flood with a damage grade between D3 and D4. The vulnerability of building types can cover ranges of two or three vulnerability classes. If the user of the scheme is untrained in engineering practice or can not decide about the extent of vulnerability affecting particularities (due the lack of information), the most likely vulnerability has to be taken.

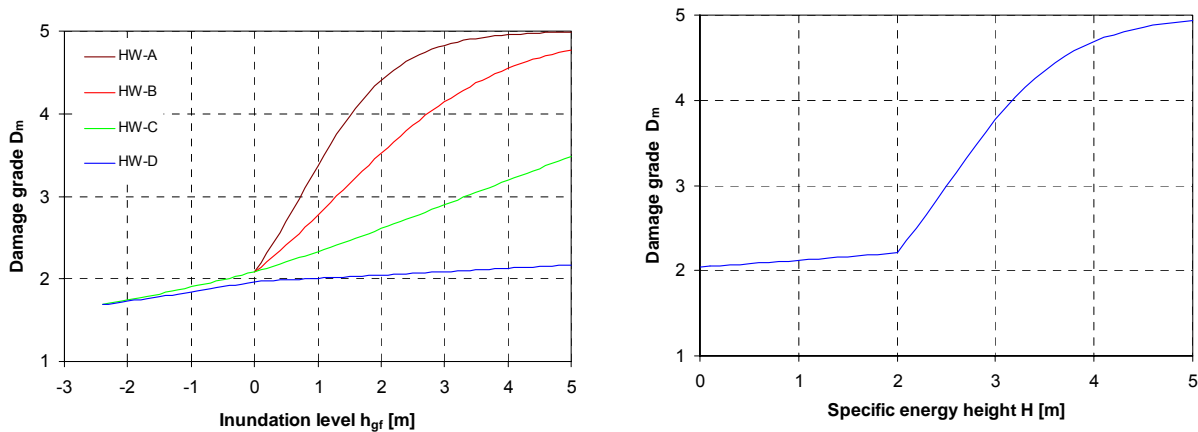
Table 2: Classification of building types in vulnerability classes and identification of ranges of scatter (on the basis of the evaluated data)

Classification of building type		Flood vulnerability class HW-VC				
Main building type	<i>short</i>	A	B	C	D	E
Clay	<i>Clay</i>	○				
Prefabricated	<i>PF</i>	—	○	—		
Framework	<i>FW</i>	—	○	⋯		
Masonry	<i>MW</i>	⋯	—	○	⋯	
Reinforced concrete	<i>RC</i>			⋯	○	
Flood resistant designed buildings	<i>FRD</i>				—	○

- Most likely vulnerability class
- Probable range
- ⋯ Range of less probable, exceptional cases

3.5 Correlation between damage grade D_i and inundation level h_{gf}

The innovative elements of the whole procedure can be subsumed and linked by a new type of Specific Vulnerability Functions (SVF), systematically developed and continuously presented in dependence on the progress of data elaboration (see Schwarz *et al.*, 2005, Schwarz and Maiwald, 2007, Maiwald, 2007). The database enables the differentiation of these functions with respect to the main structural (wall) material or, alternatively, with respect to the flood vulnerability class (see Table 2). Examples, reflecting the outcome of the combined dataset 1+2, can be taken from Figure 2a (Schwarz and Maiwald, 2007).



a) Type: $D_m = f(h_{gf}, v_{fi})$; related to Flood vulnerability classes

b) Type: $D_m = f(h_{gf}, v_{fi})$; related to the building stock (dominated by masonry structures)

Figure 2: Specific Vulnerability Functions (SVF)

3.6 Correlation between damage grade D_i and the specific energy height

For a few number of flooded areas in Saxony 2002, information about the recalculated flow velocity (v_{fi}) are submitted to the MEDIS-project group by the Regulatory Office (LTV). Without discussing the inherent model assumptions in more detail, it has to be highlighted that for a rather limited number of damage cases the relevance of flood velocity (v_{fi}) in combination with the inundation level (h_{gf}) could be investigated. The first approach related to flood intensity ($h_{gf} \times v_{fi}$) failed because no clear tendency could be established. In a second approach, the specific energy height $H = h_{gf} + (v_{fi}^2/2g)$ is predicted. Due to the limited number of samples, the building stock remains undifferentiated (being representative for masonry buildings). As a result of this rather preliminary data check, the vulnerability function for total building stock is given by Figure 2b. It can be concluded that the specific energy height H remain constant for $H < 2.0$ m; for $H > 2.0$ m, a steady increase of damage grade can be derived from the observations which is mainly attributed to the impact of increasing flow velocity (v_{fi}). From an engineering point of view, this clear tendency seems to be explainable. Further research is required to establish damage prediction models in zones where a sudden increase of flow velocity is expected due to the hydrological and topographical situation.

Results for study area 2 demonstrate that due to the implementation of flow velocity higher damage grades have to be expected (see Figure 4).

4. CASE STUDIES

4.1 Damage prediction

The innovative options and advantages of the whole procedure are demonstrated by the case studies in Figures 3, 4 and 5, respectively. It can be shown how heavily the areas of a community will be affected and where significant damage concentrations have to be expected.

Study area 1: The developed vulnerability functions are applied to the town Eilenburg. The building stock affected by the August 2002 flood was surveyed on microscale level, i.e. each building was classified with respect to its relevant structural parameters (building type, number of stories, level of floors and opening etc.). According to Table 2 the corresponding vulnerability classes are assigned. The distribution of the geo-referenced damage grades D_i is predicted for the flood scenario of 2002. Results are presented for the agglomerated mean damage grades within ATKIS land-use areas (MD_m). The predicted damage (Figure 3a) can be compared with the observed ones (Figure 3b). Local areas with unusually high vulnerability of the building stock can be identified (cf. Schwarz and Maiwald, 2007).

Study area 2: The 2002 flood caused severe structural damage in the city of Grimma. High damage grades in combination with high flow velocities occurred. Therefore, the mean damage grades (MD_m) are predicted on the basis of Specific Vulnerability Functions (SVF) of type $D_m = f(h_{gr})$ according to Figure 2a considering inundation height (h_{gr}) only (Figure 4a), and on the basis of SVF of type: $D_m = f(h_{gr}, v_{fl})$ according to Figure 2b, explicitly accounting for the effect of flow velocity (Figure 4b). The increase of damage in vicinity of the usual river bed (dark blue area) show better coincidence with the observations.

Study area 3: Similarly, damage predictions are published for the 2002 scenario and flood zones in the town Döbeln (Schwarz and Maiwald, 2007, Maiwald, 2007). Here, the town is taken as an example to present the results of the new approaches being extended to the loss prediction. The distribution of the Mean Damage Ratios (MDR) in micro- and mesoscale is illustrated by Figure 5.

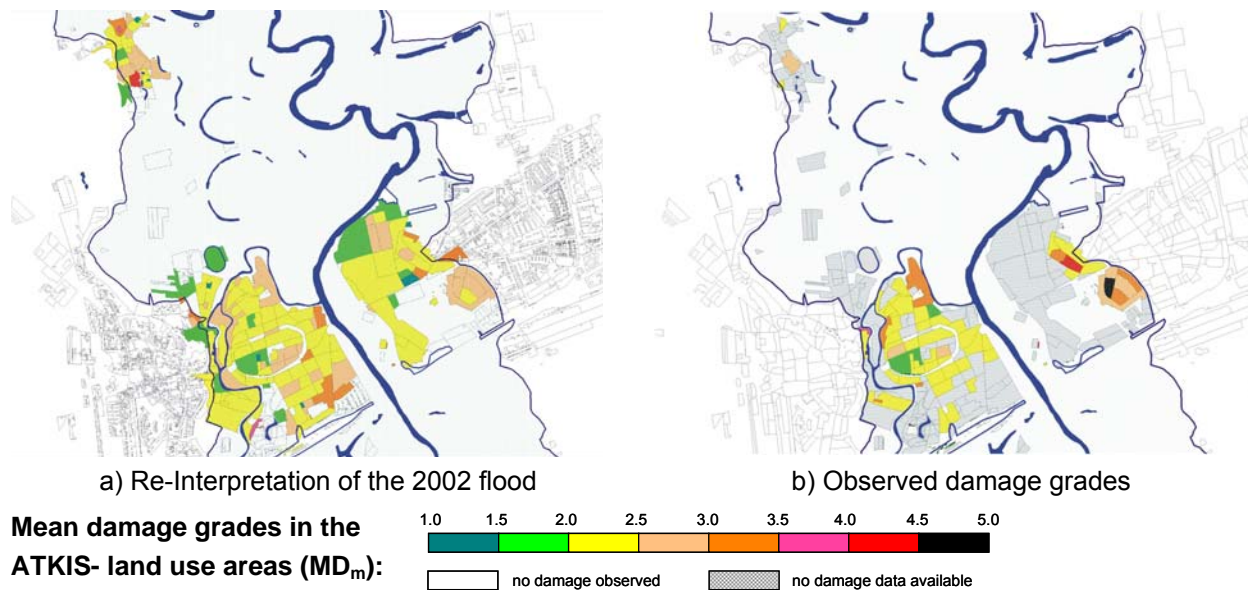


Figure 3: Observed and calculated damage grades in study area 1 (microscale prediction)

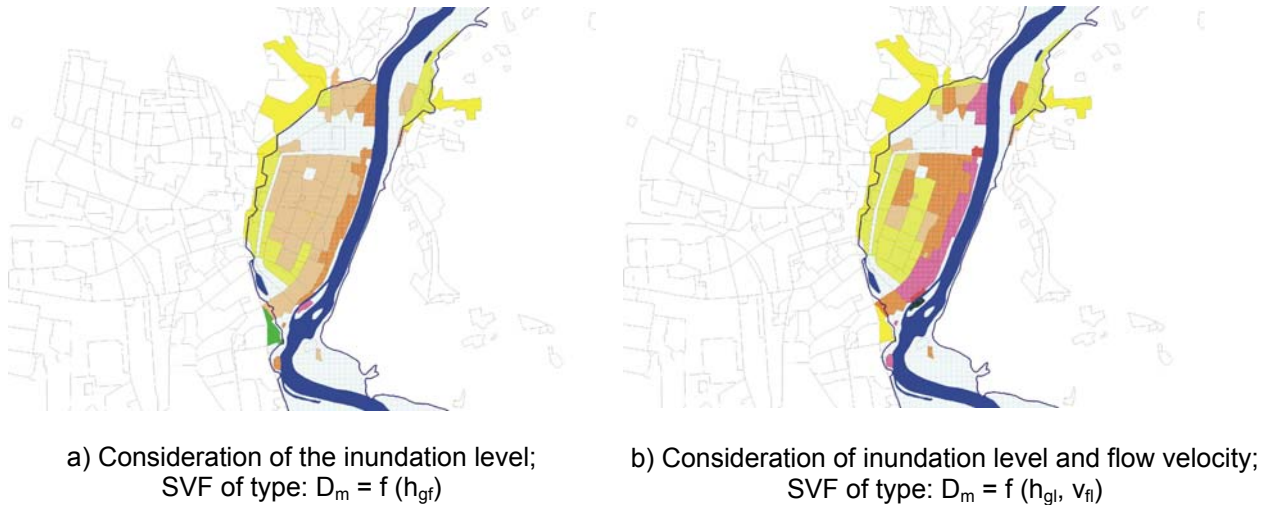


Figure 4: Calculate damage grades in study area 2 (mesoscale prediction; legend: see Figure 3)

4.2 Loss prediction

Following proposed methodology, a set of rather new types of Specific Damage Functions (for loss prediction) is under preparation. Functions refer to the building type (or flood vulnerability class) or to the grade of structural damage D_i (see Table 1). They can be refined with respect to number of stories and the presence of a cellar (Schwarz and Maiwald, 2007). At the moment, the flood model contains a modulus in which building categories according to Infas-Geodata (Infas, 2006) are supported by set of vulnerability functions. While these Geodata can be elaborated for the all German communities, meso- and macroscale prognoses are possible if data layers of the flood action parameters are available. The recent state of loss prediction using the Specific Damage Functions is illustrated for the study area 3. The loss is recalculated for the flood scenario of 2002 on the basis of the geo-referenced map of (individual) buildings (Figure 5a) as well as ATKIS-land-use areas elements (Figure 5b). The local distribution of loss is given in terms of the Mean Damage Ratio (MDR). The GIS-maps in the presented form are well suited for insurance purposes, but also for a rapid screening of the possible economic consequences.

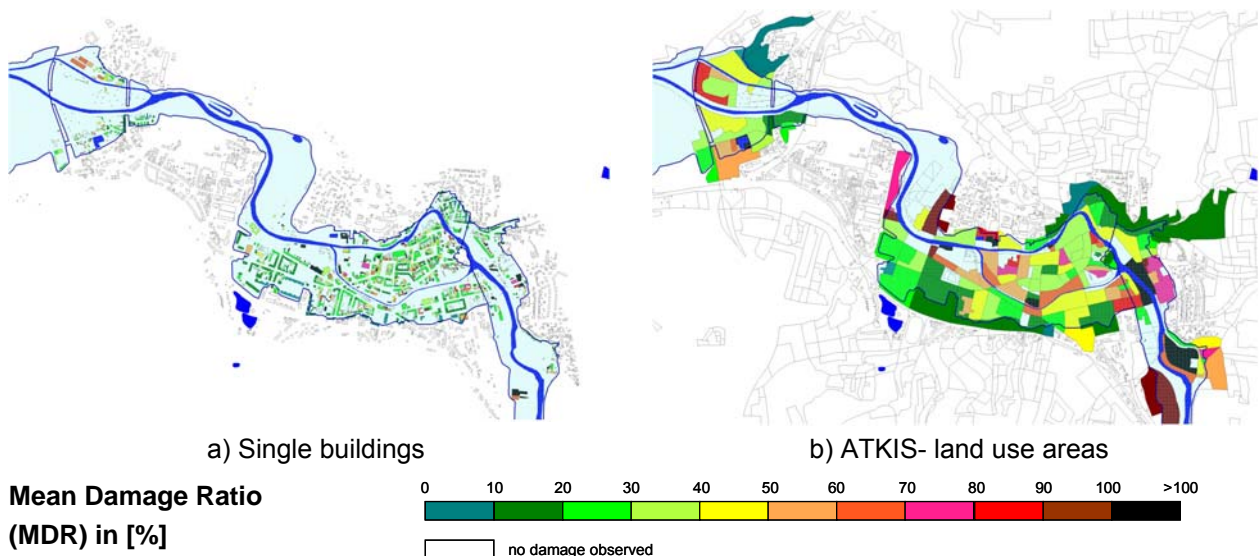


Figure 5: Calculated losses in study area 3 (microscale level)

Table 3: Comparison between reported and calculated losses for the August 2002 (Saxony) flood

Study area	Level	Reference	Losses in [Mio. €]	
			Reported ¹⁾	EDAC - loss model
1	Microscale	Residential buildings	83.3	89.9 ²⁾
		Total building stock	146.0	166.3 ²⁾
2	Mesoscale	Residential buildings	58.5	62.2 ³⁾
3	Microscale	Residential buildings	61.9	71.8 ²⁾
		Total building stock	145.0	149.4 ²⁾

1) Sächsische Aufbaubank (state 04.12.2004), note: not all damage cases in the study area included.

2) Specific Damage Functions for vulnerability classes (see Schwarz and Maiwald, 2007)

3) Specific Damage Functions for building typology according to Infas-Geodata (Infas, 2006)

The reported and calculated losses for the three study areas are summarized in Table 3. Results indicate a remarkable good agreement between the predicted and the reported losses.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

- ATKIS, 2003: Arbeitsgemeinschaft der Vermessungsverwaltungen der Länder der Bundesrepublik Deutschland, Amtliches Topographisch-Kartographisches Informationssystem: <http://www.atkis.de>
- EDAC, 2008: Damage and loss prediction model based on engineering evaluation of the vulnerability of buildings subjected to natural hazard: <http://www.edac.biz/index.php?id=47&L=1>
- Grünthal, G. (ed.), Musson, R., Schwarz, J., Stucchi, M., 1998. European Macroseismic Scale 1998. Cahiers de Centre Européen de Géodynamique et de Seismologie, Volume 15, Luxembourg.
- Infas, 2006: Infas Geodaten, Datenkatalog, Marktinformationen: Mikrogeographische Daten: http://www.infas-geodaten.de/fileadmin/media/pdf/katalog/mikro_katalog.pdf
- Maiwald, H., 2007: Ingenieurmäßige Ermittlung von Hochwasserschadenspotentialen im mikroskaligen Maßstab. Dissertation, Fakultät Bauingenieurwesen der Bauhaus-Universität Weimar
- Schwarz, J., Maiwald, H., Gerstberger, A., 2005: Quantifizierung der Schäden infolge Hochwassereinwirkung: Fallstudie Eilenburg. Bautechnik 82, 12, 845-856.
- Schwarz, J., Gerstberger, A., Maiwald, H., 2006: Engineering tools for building damage assessment under flood action – case study Saxony (Germany) 2002. EGU Vienna 2006
- Schwarz, J., Maiwald, H., 2007: Prognose der Bauwerksschädigung unter Hochwassereinwirkung. Bautechnik 84, 7, 450 - 464.
- Schwarz, J., Maiwald, H., Gerstberger, A., 2007: Flood damage prognosis considering the vulnerability of building types. European Symposium for Flood Risk Management Research (ERFM2007), Dresden.