INCORPORATION OF FLOW VELOCITY IN FLOOD DAMAGE ESTIMATION: AHR RIVER VALLEY 2021 STUDY, GERMANY

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ABSTRACT

A common practice when catastrophe model vulnerability component is being developed is the use of inundation depth as a hazard metric. However, other quantities associated with inundated waters could also yield a significant effect on estimated flood loss being widely published. The key aspect of the study is to assess the relevance of the water depth, flow velocity, and their combinations in the damage estimates done by catastrophe models. Could the flow velocity in the loss calculation process provide some benefits to the catastrophe loss modelling process? In July 2021 the western part of Germany was affected by serious flooding. The physical conditions of the inundated buildings were evaluated in the frame of the Copernicus EMS satellite-based damage assessment. The two heavily impacted areas, the towns of Schuld and Altenahr, were selected for further re-simulation aiming to test the effect of depth and velocity. In the first step, horizontal velocity and flood depth were calculated for each building using a 2D hydraulic simulation. Subsequently, structural damage models were analysed with focus on their predictive skills and variability. A force-based threshold was selected to calibrate the total loss probability, as a feature of the new vulnerability component. As a result, a hazard intensity metric expressed as combined parameter of water depth and flow velocity is finally implemented in the catastrophe model. When comparing the proposed solution with traditional depth-based approach, one can see a slight increment in the modelled monetary damage and a significantly better correlation with the observed damage identified in the study area. The embedded effect of velocity could therefore improve the accuracy and sensitivity of catastrophe flood models, particularly in high-slope areas and in events with extreme and short rainfall intensities to sudden increments in the building damage level, as assessed for the flood in the Ahr valley.
Keywords: flow velocity, flood depth, catastrophe flood modelling, structural stability.

1 INTRODUCTION

The flood damage estimation is performed by the vulnerability component of catastrophe models, employing damage curves that assign a damage ratio for a given hazard intensity. This ratio corresponds to the fraction of repair cost or monetary loss with respect to the sum insured of the asset. For the definition of the hazard parameter, it is a common practice the usage of inundation depth (Smith [1]). Nevertheless, the depth solely might not reflect the damaging processes occurring in the different flood types (Paprotny et al. [2]), such as flash floods where the flow velocity is also an important parameter in the damaging process.

The correlation between flow velocity and building damage could not be analysed independently from the inundation depth. Previous studies have recognized the energy head as a suitable parameter for the forecast of structural damage of buildings (Schwarz and Maiwald [3], Kreibich et al. [4]). Additionally, the flow velocity could influence the loss calculation process in certain contexts, such as levee-break floods or mountainous flood plains (Gallegos et al. [5]).

Several structural damage models have assessed the compound effect of inundation depth and flow velocity over different building types (Black [6], Dale et al. [7]). The models collated in Gallegos et al. [5] and Smith et al. [8] consider a threshold-type criterion for the definition of the collapse condition, being ruled by force-, energy head- or discharge-

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thresholds. In this sense, for the scenarios where the hazard intensity exceeds the threshold established by the model, the collapse or total loss of the building is expected (Smith et al. [8]).

The objective of this paper is to evaluate the influence of flow velocity in the loss modelling process, by assessing a hazard intensity metric that combines the effect of inundation depth and flow velocity and comparing it with the inundation depth-based damage curves.

2 STUDY AREA AND DATA

2.1 Study area

The Ahr river basin is situated in the Eifel region (low mountain range) in the western part of Germany. The river Ahr rises in the municipality Blankenheim at an elevation of approximately 470 m above sea level in the state of North Rhine-Westphalia. The length of the river is 85.1 km after roughly 18 km from the source it crosses the borders of federal states from North Rhine-Westphalia into Rhineland-Palatinate. The Ahr and its tributaries are the main drainage system of the eastern Eifel with a size of the catchment of about 896.4 km^2. The Ahr river, as a left tributary, flows into the Rhein at an elevation approximately 50 m above sea level (Roggenkam and Herget [9]). The Eifel region has relatively shallow soils developed on the paleozoic siliciclastic sedimentary rocks. The topography is characterized by plain surmounted by individual mountain ranges. The river network is deeply cut into valleys which usually have a V-shape, steep slope and they are narrow which could cause funnel-like effects in the flood events. The geological, pedological, and topographical conditions of the area could cause quite a fast and intensive hydrological response (Kreienkamp et al. [10]).

In July 2021, Western and Central Europe was affected by torrential rainfall caused by a slow-moving area of low-pressure named Bernd. A combination of events related to low pressure Bernd, high moisture in the air, which was constantly tapped from the Mediterranean Sea, and stop of movement almost for four consecutive days, led to extreme rainfall. Many areas of western Germany recorded rainfall rates that exceeded a 1-in-100-year return period in some areas even 1-in-1000-year return period. Unfortunately, the soil was already almost saturated from previous rainfall events and a combination of all factors caused catastrophic floods on the Ahr river but also on the other parts of Germany and Europe. This event is ranked among the deadliest natural disasters in modern German history and caused a huge financial loss. The towns Schuld and Altenburg, which are located on the Ahr river and were heavily affected, were selected for a detailed analysis (Cat Alert [11]).

2.2 Copernicus EMS grading assessment

Copernicus is an EU programme aimed to provide information services based on satellite Earth observation and in situ data. The Copernicus Emergency Management Service (CEMS) provide mapping service in cases of natural disasters, human-made emergencies, and humanitarian crises during all phases of the emergency management cycle (forecast, notifies, monitor) throughout the world. The satellite imagery and other geospatial data are used for developing the products. The rapid mapping activations could have four kind of products: reference map, first estimate map, delineation map, and grading map. This geospatial information or products are provided within hours or a few days after disaster (Dorati et al. [12], CEMS [13]).

The grading map is based on post-event imagery and provides an assessment of the damage grade and its spatial distribution. Unfortunately, it is not possible to use the existing methodologies for damage assessment of building structures because most of them are designed for ground-based field evaluations. The CEMS for rapid damage assessment of building structures involved, as a starting point, the European Macroseismic Scale 1998 (EMS-98). Due to challenges and limitations related to geospatially based damage assessment as the bird's-eye view, the image geometric resolution, the radiometric resolution, and the subjectivity of the interpretation the CEMS adapted the EMS-98 classes. The categories were aggregated and simplified to reflect the inherent limitations of the technology adopted (remotely sensed imagery) and time constraints in place (rapid, near real-time). Two additional categories (possibly damage, no visible damage) are added to consider the intrinsic uncertainty of the methodology. The CEMS products are made from remotely sensed imagery and in almost real-time, not as ground observation data therefore it is necessary to take into account a certain uncertainty in their use (Dorati et al. [12], CEMS [13]).

Table 1: Comparison of Copernicus EMS and EMS-98 classes for damage assessment of buildings [12].

Copernicus EMS classes		**EMS-98 classes**
No visible damage	(green)	Grade 0: No damage
Possibly damaged	(yellow)	It refers to cases when the confidence level of the interpretation is slightly lower (e.g. bad image quality)
Damaged	(orange)	Grade 1: Negligible to slight damage
		Grade 2: Moderate damage
		Grade 3: Substantial to heavy damage
Destroyed	(red)	Grade 4: Very heavy damage
		Grade 5: Destruction

The EMSR517 flood in Western Germany is a product of the CEMS Rapid Mapping Service to monitor the flood evolution after heavy rain which affected federal state Rhineland-Palatinate. This product consists of 11 delineation products (43 maps) and 16 grading products (37 maps), particularly the [EMSR517] Bad Neuenahr-Ahrweiler: Grading Product, Monitoring 1, version 3, release 1, RTP Map#01 published on 11 August 2021 was used in this study. The number of buildings classified according to CEMS classes is 753 destroyed, 5078 damaged and 1175 possibly damage in this area (CEMS [13]).

2.3 2D hydraulic simulation

Hydraulic simulation of the July 2021 flood was done as 2D model with 10m resolution by HPC TUFLOW software from BMT [14]. TUFLOW is a computer program for simulating depth-averaged, one and two-dimensional free-surface flows such. Flow regimes are handled by adaptation of the Saint Venant Equations and Shallow Water Equations with momentum and continuity equations for free flow.

Source of elevations was "DGM10 – Digitales Geländemodell Gitterweite 10 m". Shape of buildings were used from the OSM [15]. The simulation considered 50% blockage of bridges. Flows and water surface elevations were considered based on analysis of hydrology data from webpages of Landesamt für Umwelt (LfU) [16] and Bundesanstalt für Gewässerkunde (BfG) [17], which were publicly available in August 2021 (limited number of records; without detailed verification of providers). The record of the gauging station Müsch located in the Ahr river valley is shown on Fig. 1 as an example.

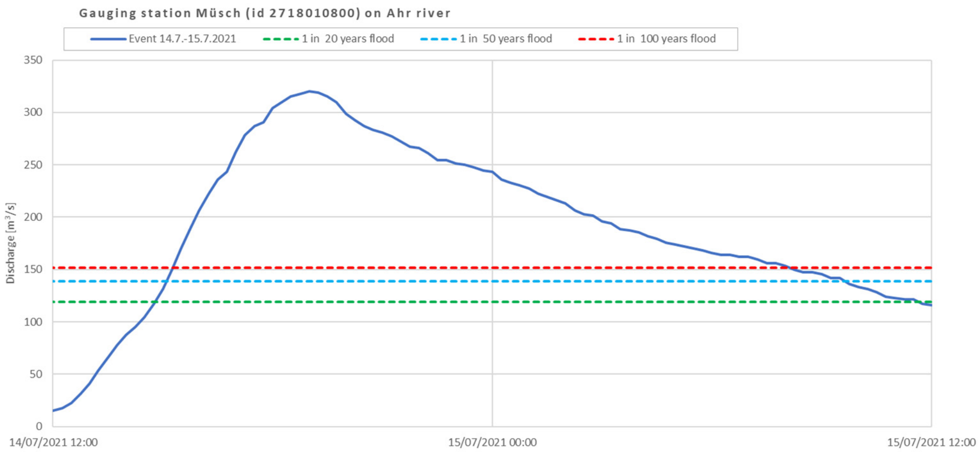

Figure 1: Gauging station Müsch on Ahr river – Discharges during flood event 14–15 July 2021 and official discharges for flood of return period 20, 50 and 100 years. *(Source: Values from Landesamt für Umwelt (LfU) [16].)*

The values of water depth–flow velocity for each one of the building's locations are obtained from the hydraulic simulation. In Fig. 2, each point of the scatter represents one of the buildings mapped by Copernicus EMS. Additionally, the plot shows the damage grade (possibly damaged, damaged, destroyed) assigned to each building of the dataset.

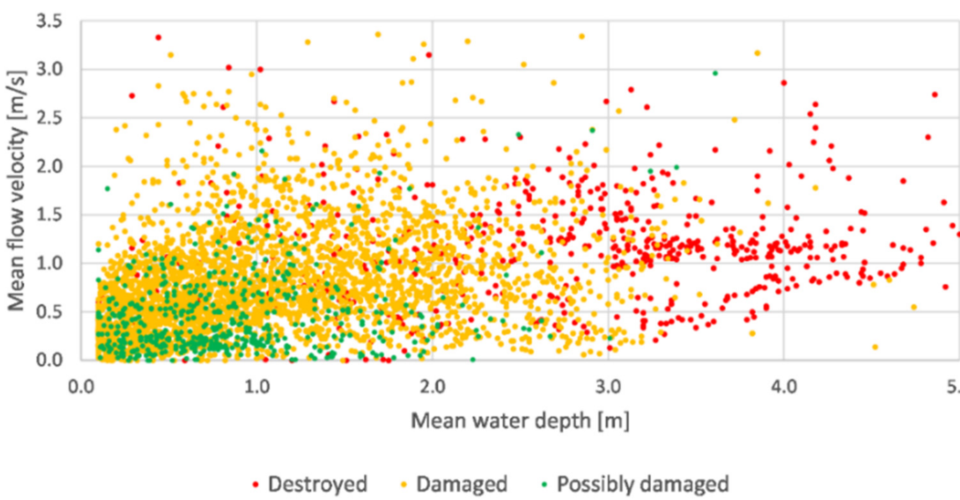

Figure 2: Water depth and flow velocity calculated for each building in the area of the CEMS activation and their corresponding damage grade.

3 METHODS

3.1 Structural stability of buildings

The stability of buildings could be threatened due to several mechanisms, including lateral pressures from depth differentials and flood velocities, buoyancy, debris impact, and scour. These aspects have been analysed in the development of different damage models proposed in the scientific literature (Gallegos et al. [5]). In Table 2, different damage threshold-type criteria are shown. The models are defined based on either water depth h, flow velocity V, discharge per unit width q, energy head E, and force F (per unit width and fluid density).

- Discharge per unit width

$$q = hV, \tag{1}$$

- Energy head

$$E = h + V^2/2g, \tag{2}$$

- Indicator of flow force

$$F = hV^2. \tag{3}$$

Table 2: Review of existing structural damage models.

Failure criteria	**Country**	**Threshold definition**	**Construction type**	**Ref.**
WRL Light Str.	Australia	$q > 1\,m^2/s$, $h > 2m$, $V > 2\,m/s$	–	[8]
WRL Max.		$q > 4\,m^2/s$, $h > 4m$, $V > 4\,m/s$		
Black, 1 storey	USA	Fit of exponential decay function [5]	Wood frame	[6], [5]
Black, 2 storeys				
Clausen and Clark	UK	$q > 7\,m^2/s$, $V > 2\,m/s$	–	[5]
Kreibich, et al., Energy-based	Germany	$E > 2m$	–	[4], [5]
Kreibich, et al., Depth-based		$h > 2m$		
Kreibich, et al., Discharge-based		$q > 1.5\,m^2/s$		
Kreibich, et al., Force-based		$F > 2\,m^3/s^2$		
CH2M, 1 storey	USA	$F > 7.6\,m^3/s^2$, $h > 3m$	Wood frame	[5]
CH2M, 2 storeys		$F > 7.6\,m^3/s^2$, $h > 4.5m$		
Gallegos et al., Moderate	USA	$F > 0.75\,m^3/s^2$	Wood framed	[5]
QRA	Australia	$q > 1.2\,m^2/s$, $h > 2m$, $V > 2\,m/s$	–	[8], [18]
NCC Light Str.	Australia	$q > 1\,m^2/s$, $h > 2m$, $V > 2\,m/s$	Masonry, wood	[8], [19]
NCC Heavy Str.		$q > 2.5\,m^2/s$, $h > 2.5m$, $V > 2.5\,m/s$	Steel frame, concrete	

The structural damage models collated in Table 2 are plotted in Fig. 3 to allow the comparison of the curves. The figure highlights the overall uncertainty in the matter of building stability under flooding conditions (Smith et al. [8]). The difference between the models is due to the characteristics of the buildings being assessed in each study. The vulnerability of the buildings is linked to their construction type, which play an important role in the definition of the threshold from which the building is prone to collapse.

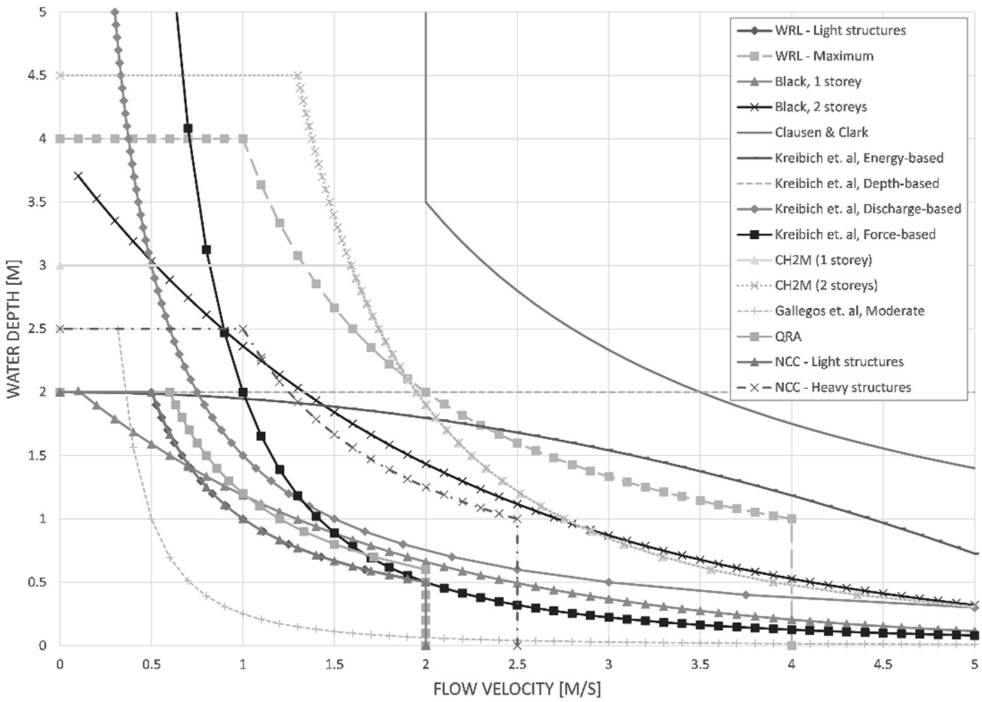

Figure 3: Comparison of building stability curves considered for this study. The failure condition is expected for the depth–velocity combination above the curves. *(Source: Adapted from Gallegos et al. [5].)*

To evaluate the performance of the models, regarding their capability to predict the failure of the buildings in the study area, the number of hits H, misses M, false alarms FA, and correct rejections Z are quantified. The definition of each one of these parameters is shown in Table 3. The failure condition of the building is taken from the class Destroyed from the Copernicus EMS damage assessment. The model outcome corresponds to the predicted failure or non-failure of the buildings analysed with each stability curve (Gallegos et al. [5], Baldwin and Kain [20]).

Table 3: Contingency table for assessment of predictive skill of building stability curves.

	Observed condition – Copernicus EMS grading	
Forecast – Model outcome	Failure	No failure
Failure predicted	Hit (H)	False alarm (FA)
Failure non predicted	Miss (M)	Correct rejection (Z)

Furthermore, the following metrics were computed (eqns (4)–(8)):

- Probability of detection (POD)

$$POD = H/(H + M), \quad (4)$$

- Probability of false detection (POFD)

$$PFOD = FA/(Z + FA), \quad (5)$$

- False alarm ratio (FAR)

$$FAR = FA/(H + FA), \quad (6)$$

- Bias (B)

$$B = (H + FA)/(H + M), \quad (7)$$

- Skill (S)

$$S = POD - POFD. \quad (8)$$

3.2 Correlation analysis and hazard intensity metric

The analysis of the dependencies between the hazard metrics and their dependency with the structural damage is performed for the dataset of impact parameters on the buildings in the study area (Fig. 2).

As an outcome of the failure condition assessment and the analysis of the correlation between the hazard parameters and the structural damage, different alternatives for the hazard intensity metric as a function of water depth and flow velocity are tested. The output regarding the effect on the monetary losses is then evaluated by comparison with the losses obtained with the depth-based approach.

4 RESULTS AND DISCUSSION

4.1 Performance of stability models

The capacity to forecast the structural failure of each model is reflected in the damage metrics shown in Table 4. Several models reach a skill value of more than 0.40, being the highest skill value (S = 0.48) obtained with the discharge-based models WRL – Light structures and QRA. Nevertheless, both models are within the ones with the greatest bias. The force- and energy-based models proposed by Kreibich et al. [4] reach similar metrics of skill, FAR and bias. Additionally, discharge-based model NCC – Heavy structures performed analogously. Finally, we could not conclude that even energy, discharge, or force models account for a better performance than the others.

The skill values obtained are low in comparison with previous studies, such as Gallegos et al. [5]. This could be related to many uncertainty factors, including the damage assessment performed by photo interpretation, that does not reach the same output as an evaluation in the field (ground truth). Furthermore, the category destroyed of the CEMS grading does not correspond uniquely with washout buildings, but also considers the buildings in grade 4 of the EMS-98 classes, as shown in Table 1. Additionally, it is expected to have some discrepancies regarding the hydraulic simulation with respect to the real event.

The broad range of skill values obtained follows the high variability in the damage models shown in Fig. 3. As an example, Fig. 4 shows the zones of stability failure predicted by three of the models for the Schuld municipality. The model WRL for light structures proposed by Smith et al. [8] gives the greatest damage zone, covering most of the buildings identified as

Table 4: Predictive skill, false alarm ratio and bias for each damage model applied in the Ahr river.

	Predictive skill (S)	False alarm ratio (FAR)	Bias (B)
WRL – Light structures	0.48	0.89	7.56
WRL – Maximum	0.26	0.62	0.75
Black, 1 storey	0.46	0.89	7.21
Black, 2 storeys	0.39	0.77	2.06
Clausen and Clark	0.06	0.52	0.13
Kreibich et al., Energy-based	0.42	0.83	3.44
Kreibich et al., Depth-based	0.40	0.82	3.11
Kreibich et al., Discharge-based	0.45	0.86	4.65
Kreibich et al., Force-based	0.42	0.84	3.74
CH2M (1 storey)	0.31	0.65	0.98
CH2M (2 storeys)	0.22	0.61	0.62
Gallegos et al., Moderate	0.42	0.89	7.20
QRA	0.48	0.88	6.65
NCC – Light structures	0.48	0.89	7.56
NCC – Heavy structures	0.47	0.79	2.88

Figure 4: Zones of stability failure predicted by the damage models for the Schuld area.

destroyed by the Copernicus grading assessment. Nevertheless, some of the damaged buildings are also included in this zone. Furthermore, a smaller area is obtained with the model proposed by Kreibich et al. [4], while the CH2M model is not capable to map the area of the destroyed buildings, underestimating the damage zone.

A unitary force-based model is selected to be implemented in the model. The calibration of the optimal force threshold is performed based on the expected chance of total loss (COTL). In this sense, the flow velocity influences the estimation of the proportion of buildings that could reach a failure condition. The COTL is further applied in the damage function, corresponding to the condition of mean damage ratio equal to 1.

4.2 Correlation and predictive skill analysis

The water depth has a significant effect on the losses. The depth above approximately 2 m has a big chance of destroying the buildings (see Figs 2 and 5). The threshold when the flow velocity has an impact on the building structural damage could be approximately 1 m/s but there is no clear limit for the flow velocity between damaged and destroyed buildings.

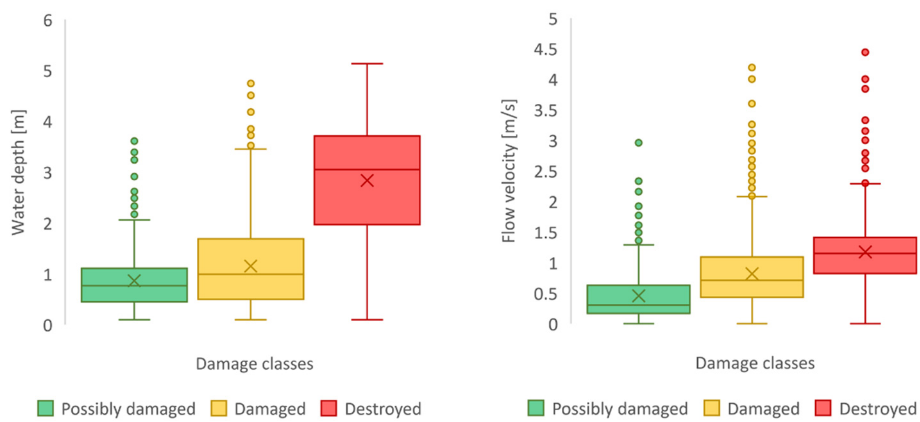

Figure 5: Boxplots for the calculated water depth and flow velocity at the building's location, categorized by damage classes.

As shown in Table 5, the flow velocity has the strongest correlation relationship with the indicator flow force and the intensity. The water depth has the strongest correlation with the energy head, as the potential energy is the dominant parameter for the energy head.

Table 5: Correlation between the impact parameters.

	Flow velocity (m/s)	Water depth (m)	Energy head (m)	Indicator flow force (m^3/s)	Intensity (m^2/s)
Flow velocity (m/s)	1.00	0.35	0.40	0.92	0.82
Water depth (m)		1.00	0.99	0.66	0.80
Energy head (m)			1.00	0.70	0.83
Indicator for flow force (m^3/s)				1.00	0.97
Intensity (m^2/s)					1.00

For each hazard parameters, minimum thresholds for experiencing certain level of damage were established. The skill of each one of these impact parameters to identify the damage class of the buildings in the municipalities of Altenahr and Schuld is shown in Table 6. The flow velocity has the lowest skill value. In contrast, energy head, which considers the effect of the water depth and flow velocity (potential and the kinetic energy, respectively), reached the highest predictive capability. It is evidenced that, for these specific locations, the flow velocity as part of the energy head has impact on the damage of the buildings.

Table 6: Predictive skill, false alarm ratio and bias for each alternative of hazard intensity applied in the municipalities of Altenahr and Schuld.

Location		Flow velocity (m/s)	Water depth (m)	Energy head (m)	Indicator flow force (m^3/s)	Intensity (m^2/s)
Altenahr (n = 49)	Skill (S)	0.03	0.24	0.43	0.16	0.32
	FAR	0.33	0.29	0.21	0.29	0.26
	Bias (B)	0.75	1.41	1.06	0.97	1.22
Schuld (n = 41)	Skill (S)	0.07	0.21	0.26	0.16	0.21
	FAR	0.47	0.33	0.35	0.36	0.33
	Bias (B)	0.85	0.60	0.85	0.55	0.60

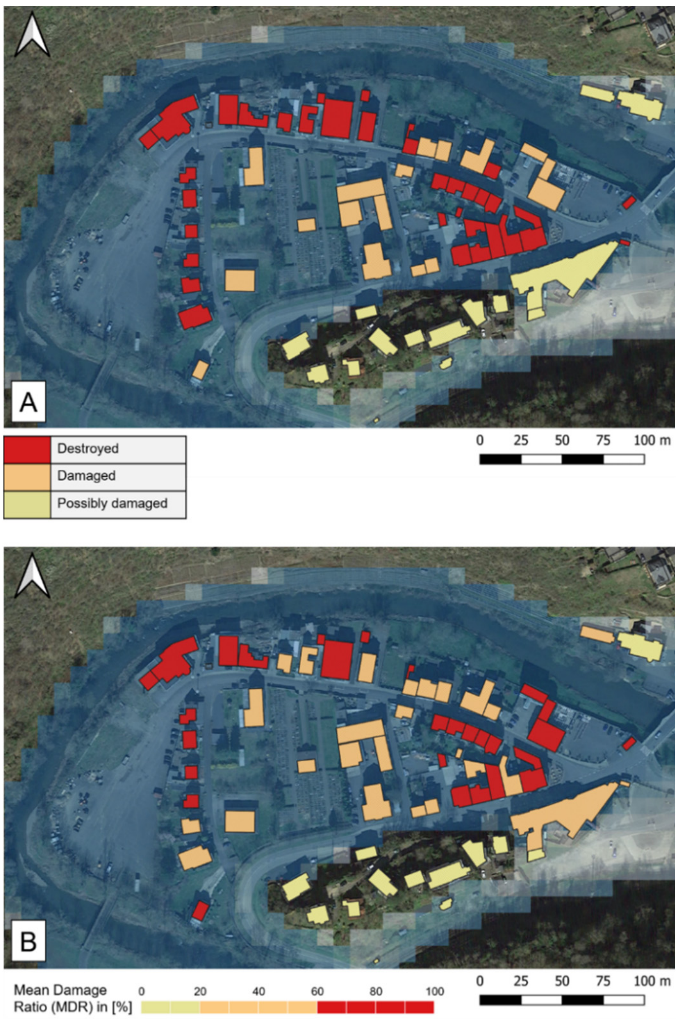

Figure 6: Location: Altenahr municipality. (A) Copernicus EMS damage assessment; and (B) Application of the hazard intensity metric as a function of water depth and flow velocity. MDR = f (depth, velocity).

Further research of different types of floods and their impact on the structural damage of buildings is necessary. The methodology applied (for the determination of the damage grade or in the hydraulic simulation) or the influence of the impact parameters not considered in this study (impact of debris or flood duration) represent sources of uncertainty in the analysis.

4.3 Performance of the hazard intensity metric

The hazard metric is finally implemented in the catastrophe model. Due to the lack of information about the specific buildings, for this study the building stock remains undifferentiated, considering masonry buildings for the damage curve definition. For the Altenahr municipality, in Fig. 6 a partially good agreement is reached between the Copernicus EMS damage assessment and the distribution of expected monetary loss given by the mean damage ratio.

Furthermore, it was obtained an increment of 2%–4% on the expected monetary loss in comparison with the depth-based approach. The slight increment in the monetary loss implies a small impact in the probable maximum loss (PML) calculated by the model. Nevertheless, the impact is localized in small part of the floodplain, particularly high slope areas, being the effect on the average annual loss (AAL) significant for these specific locations and allowing a better estimation in the underwriting process.

5 CONCLUSIONS

The flow velocity incorporation in the flood damage estimation process is achieved based on the study of its influence on the stability of the buildings and the dependency of the structural damage and the hazard intensity parameters.

Regarding the existing structural damage models, the highest skill in the prediction of the destroyed buildings was obtained by the WRL – Light structures model, while the model proposed by Clausen and Clark has the worst skill value. Nevertheless, it was recognized that in most of the cases, high skill models implied high bias, with an overestimation in the number of destroyed buildings.

The results from the analysis performed in this study showed that the energy head is a suitable parameter for the forecasting of structural damage, as suggested by Kreibich et al. [4]. Further study in this matter is necessary, including also different flood types and areas with different morphological conditions.

The hazard intensity metric defined based on water depth and flow velocity implemented in the catastrophe model derived in a slight increment in the monetary losses compared to the depth-based approach. This difference could increase in the case of high-slope areas.

The vulnerability component developed in this paper aimed to consider the combined effects of water depth and flow velocity on the monetary damage that a building can undergo. Furthermore, the construction type of a building should be considered since it is related to its vulnerability and probability of collapse.

There are many uncertainty factors faced in this study, including limitations of the Copernicus EMS product and the hydraulic simulation to reflect the real event conditions. Finally, the current paper is part of an ongoing study. An evaluation of the transferability of the model and calibration of the monetary losses would generate further improvements in the modelling process.

REFERENCES

[1] Smith, D.I., Flood damage estimation: A review of urban stage damage curves and loss functions. *Water SA*, **20**(3), pp. 231–238, 1994.

[2] Paprotny, D., Kreibich, H., Morales-Nápoles, O., Wagenaar, D., Castellarin, A., Carisi, F., Bertin, X., Merz, B. & Schröter, K., A probabilistic approach to estimating residential losses from different flood types. *Natural Hazards*, **105**, pp. 2569–2601, 2021.

[3] Schwarz, J. & Maiwald, H., Damage and loss prediction model based on the vulnerability of building types. *4th International Symposium on Flood Defence*, 2008.

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

[5] Gallegos, H., Schubert, J. & Sanders, B., Structural damage prediction in a high-velocity urban dam-break flood: Field-scale assessment of predictive skill. *Journal of Engineering Mechanics*, **138**(10), pp. 1249–1262, 2012.

[6] Black, R., Flood proofing rural residences. A Project Agnes report, Cornell University: New York, 1975.

[7] Dale, K., Edwards, M., Middelmann, M. & Zoppou, C., Structural flood vulnerability and the Australianisation of Black's curves. *Proceedings of the Risk Conference*, 2004.

[8] Smith, G.P., Davey, E.K. & Cox, R.J., Flood hazard. WRL Technical Report 2014/07, UNSW: New South Wales, 2014.

[9] Roggenkamp, T. & Herget, J., Reconstructing peak discharges of historic floods of the river Ahr, Germany. *Erdkunde*, **68**(1), pp. 49–59, 2014.

[10] Kreienkamp, F., Philip, S.Y., Tradowsky, J.S., Kew, S.F., Lorenz, P., Arrighi, J. & Wanders, N., Rapid attribution of heavy rainfall events leading to the severe flooding in Western Europe during July 2021. *World Weather Attribution*, p. 51, 2021.

[11] Cat Alert, Western and Central Europe Floods, Impact Forecasting, Aon, 2021.

[12] Dorati C., Kucera, J., Marí i Rivero I. & Wania, A., Product User Manual of Copernicus EMS Rapid Mapping. JRC Technical Report JRC111889, Joint Research Centre, 2018.

[13] Copernicus Emergency Management Service (CEMS). https://emergency.copernicus.eu/. Accessed on: 25 Feb. 2022.

[14] BMT, TUFLOW Classic/HPC User Manual, Build 2018-03-AD. BMT: Australia, p. 723, 2018

[15] OSM, https://www.openstreetmap.org/.

[16] LfU, http://213.139.159.46/prj-wwvauskunft/projects/messstellen/wasserstand.

[17] BfG, https://www.bafg.de/DE/06_Info_Service/01_Wasserstaende/wasserstaende_node.html.

[18] Queensland Reconstruction Authority, Planning for stronger, more resilient floodplains. https://www.qra.qld.gov.au/publications-and-maps/building-and-planning-guides. Accessed on: 25 Feb. 2022.

[19] Newcastle City Council, Newcastle flood policy 2003: A technical manual, 2003.

[20] Baldwin, M. & Kain, J., Sensitivity of several performance measures to displacement error, bias, and event frequency. *Weather Forecast.*, **21**(4), pp. 636–648, 2006.