INSYDE: a synthetic, probabilistic flood damage model based on explicit cost analysis

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Abstract. Methodologies to estimate economic flood damages are increasingly important for flood risk assessment and management. In this work, we present a new synthetic flood damage model based on a component-by-component analysis of physical damage to buildings. The damage functions are designed using an expert-based approach with the support of existing scientific and technical literature, and have been calibrated with loss adjustment studies and damage surveys carried out for past flood events in Italy. The model structure is designed to be transparent and flexible and therefore it can be applied in different geographical contexts, and adapted to the actual knowledge of hazard and vulnerability variables.

The model has been tested in a recent flood event in Northern Italy. Validation results provided good estimates of post-event damages, with better performances than most damage models available in the literature. In addition, a local sensitivity analysis has been performed, in order to identify the hazard variables that have more influence on damage assessment results.

1 Introduction

Flood damage evaluation is nowadays a crucial component of any strategy of flood risk mitigation and management (Messner and Meyer, 2006; Messner et al., 2007; Merz et al., 2010). In particular, models and methodologies to estimate economic damages are key for evaluating and comparing flood mitigation measures and for defining flood risk management plans (Bouwer et al., 2013; Schröter et al, 2014).

Available damage models can be classified in two main classes: empirical and synthetic models (Smith, 1994; Merz et al., 2010). Empirical models use damage datasets collected from past flood events to link vulnerability and hazard variables to damage (data-driven approaches). Synthetic models adopt a more conceptual approach, and use hypotheses and assumptions on damage mechanisms (what-if analysis) to derive damage functions (expert-based approach).

Despite their growing importance, there are still relevant issues in the application of flood damage models (Handmer, 2003; Meyer et al., 2013). First, the relative scarcity of observed damage datasets is a relevant obstacle in developing and improving existing models. Models based on data-driven approaches are especially prone to this issue, as they require specific calibration to be applied in different contexts (Merz et al., 2010; Bubeck and Kreibich, 2011). Synthetic models, adopting conceptual, expert-based assumptions of hazard-damage relationships, are less dependent on datasets for model derivation, though they still require additional data for calibration and validation (Smith, 1994; Merz et al., 2010).

Second, even where reliable and comprehensive datasets are available, it is generally not possible to extrapolate adequate damage functions, due to the well-known complexity of damage mechanisms (Andrè et al., 2013; Scorzini and Frank, 2015). Damage computation methods based on probabilistic approaches might offer a solution to this issue (Schröter et al, 2014), yet this research topic is still relatively unanswered in literature.

Third, the evaluation of flood mitigation measures requires methodologies to estimate economic damages at both the micro (e.g. building-scale strategies for vulnerability reduction) and the meso scale (e.g. spatial planning strategies) (Schröter et al., 2014). When micro-scale strategies are considered, empirical models are less suitable because the model structure generally considers few explicative variables. For buildings these typically include the water depth, the building structure and the number of floors (Messner and Meyer, 2006; Schröter et al., 2014); as a consequence, it is not possible to evaluate the effect of the full range of mitigation strategies available like the use of permeable materials, the moving of vulnerable components, etc. Synthetic models can overcome this limitation, as their level of complexity can be designed to adapt to the required detail. Still, these models are often affected by a lack of transparency. In many cases, the rationale behind model development (e.g. assumptions, mechanisms considered, built-in parameters) is not clearly presented, and relevant variables to be used are not explained, which limits applicability and transferability, as well as possible improvements (Scorzini and Frank, 2015).

Given this framework, in this paper we propose a probabilistic methodology to derive synthetic damage curves for residential buildings, called INSYDE (IN-depth SYnthetic model for flood Damage Estimation). The method is based on an explicit component-by-component analysis of physical damages to buildings, which takes into account available knowledge on damage mechanisms. INSYDE is transparent and can be applied in different contexts. Implemented functions and values are clearly explained so that they can be totally or partly modified according to the physical context in which the model is applied. On the other hand, the methodology allows for different levels of detail in the analysis, hence the damage model can be adapted to the actual knowledge of relevant hazard and vulnerability variables. As such, the methodology is suitable for a variety of applications:

- characterisation and derivation of damage curves for residential building types (ex-ante vulnerability analysis);
- post-event damage estimation (ex-post vulnerability analysis);
- analysis of uncertainty sources in damage estimation.

The damage functions composing the model have been designed using an expert-based approach with the support of existing scientific and technical literature. They were then calibrated considering loss adjustment studies and damage surveys carried out for past flood events in Italy. It is important to note that the current version presented in this paper is limited to residential building damage estimation. The general methodology, however, can be extended to other types of assets, such as damage to commercial or industrial buildings.

Subsequently, the model has been validated against damage estimations collected for a recent flood event in Northern Italy, and compared with the results provided by several literature damage models. Finally, we performed a sensitivity analysis of the model hazard parameters, in order to explore in more detail the model behaviour and quantify the influence of each hazard parameter. The results and relevant findings are discussed in order to highlight strengths and weaknesses of the proposed model.

2 Methodology

INSYDE adopts a synthetic approach consisting in the simulated, step-by-step inundation of residential buildings and in the evaluation of the corresponding damage, based on building and hazard features. Such a methodology can be also referred to as a what-if analysis.

Damages are first modelled component by component using physically based mathematical functions, and then converted into monetary terms, using full replacement costs derived from reference price lists.

In detail, the overall damage (*D*) to each single building is decomposed in different damage components (C_i), as follows:

$$\mathrm{D} = \sum_{i=1}^{n} \mathrm{C}_i = \sum_{i=1}^{n} \sum_{j=1}^{m_i} C_{ij} \tag{1}$$

where C_i includes clean-up and removal costs, structural damage, non-structural damage, damage to finishing elements, damage to windows and doors, and damage to building systems, and n is the total number of components used to define the damage. Each component C_i is subdivided into m_i different subcomponents C_{ij}, specifically referring to the reparation of the damaged elements or to their removal and replacement. The complete list of components and subcomponents is presented in Table 1.

For each subcomponent, a mathematical function describing the damage mechanism and associated cost is formulated, considering expert-based knowledge as well as available technical and scientific documentation. The general formulation can be described as follows:

$$C_{ij} = f(\text{Event features, Building characteristics, Unit prices}) \tag{2}$$

where:

- *Event features* include all the physical variables describing the flood event at the building location, e.g. maximum external and internal water depth, flood duration, water quality (presence of contaminants) and sediment load.
- *Building characteristics* include all the variables describing features and geometry of the building. Building features affect damage estimation either by modifying the functions describing damage mechanisms (e.g. system distribution, building structure) or by affecting the unit prices of the building components by a certain factor (e.g. building type, finishing level). On the other hand, the geometrical properties of the building (e.g. footprint area, number of floors) are used in the estimation of the extension of damage to each of the building components.
- *Unit prices* refer to the cost of replacement or reparation of the building components per unit of measure (e.g. doors removal cost per square meter, pavement replacement cost per square meter). For the present study, unit prices are derived from Italian price lists for the year 2013 (default values are shown in Table A1 of the Annex).

The cost for each subcomponent is determined by the *extension* (*Ext*) and the *unit price* (*Up*). The former is the measure of the physical dimension of the damage (e.g. m^2 of plaster damaged), and depends on the event features and building characteristics. We can therefore refer to:

$$C_{ij} = Extension_{ij} \cdot UnitPrice_{ij} = Ext \cdot Up \quad (3)$$

This distinction is useful for the model generalisation. The extension of the damage is determined only by the physical effects that the flood event cause to the building, therefore the same approach can be applied in different countries or geographic areas, provided that the local characteristics of buildings are accounted for. Unit prices, instead, vary from country to country or even within a country, but on the other hand they can be referred to standard or default unit prices in official publications. Therefore, with this approach, local price values are well identified and can be easily replaced with more suitable ones.

Tables 2 and 3 describe in detail the *Event features* and *Building characteristics* parameters, their unit of measurement, their range and the default values in case no information is supplied to the model. The damage functions and the general assumptions for all the damage sub-components are reported in the Annex, while Table 1 synthesises the *Event features* and *Building characteristics* considered for each subcomponent function. The variables listed in Tables 2 and 3 can directly affect damage estimation, in terms of extension, or indirectly by influencing other variables, like YY (year of construction) on PD (heating distribution type) or FA (footprint area) on IA (internal area). Another important aspect of the proposed approach is that several of the damage mechanisms are modelled using probabilistic functions, rather than deterministic ones. The motivation is that, even if the damage mechanism for certain components is known, it is impossible to deterministically define, for certain hazard variables, a threshold below which no damage occurs and above which it does. This is because there are uncertainties due to flood event and building characteristics that are not included in the model or cannot be quantified a priori. For instance, it is known that plaster is usually not damaged for short duration flood events, while replacement might be necessary in case of a long duration flood (Penning-Rowsell et al., 2005). However, it is not possible to define a deterministic threshold for the variable "flood duration", because it depends on variables like the type of plaster, the season in which the flood occurs, and so on. In practice, these types of variables are usually not obtainable, or if they are, it is not possible to have a clear understanding on how they affect the damage mechanism. As an example, one could assume that the threshold value for plaster replacement is 12 hours. However, it might happen that in reality, the plaster needs to be replaced even if the flood duration is lower than that (e.g. 11 hours); conversely, it is possible that the plaster is not damaged for a flood with a longer duration (13 hours, for example), because of the factors described above.

To account for these uncertainties, the model considers that for some of the building components, given a certain flood hazard variable, there is a probability that damage might occur. This approach is similar to the one widely used in the field of seismic vulnerability assessment (e.g. Rossetto and Elnashai, 2003; Rota et al., 2008), in which for a given intensity measure there are various possible damage ratios r_s, each with its probability of occurrence p_s, represented by fragility curves. By combining them, the expected damage ratios $E[R]$ can be obtained.

In the case of probabilistic functions, eq. (3) becomes:

$$C_{ij} = Extension_{ij} \cdot UnitPrice_{ij} \cdot E[R] \quad (4)$$

In the case of INSYDE, for most components it is assumed that if damage occurs, replacement is necessary. In these cases, no intermediate damage levels, such as slight or extensive damage, are considered. Thus, there are only two possible damage levels – either no damage (r_0=0) or replacement (r_1=1). In this case, the expected damage ratio $E[R]$ is given directly by the probability of occurrence of damage, as shown in Eq. (5):

$$E[R] = r_0 p_0 + r_1 p_1 = 0 \cdot p_0 + 1 \cdot p_1 = p_1 \quad (5)$$

The expected damage is then obtained by multiplying the replacement cost of the component by its expected damage ratio, as shown in Eq. (4).

The distribution of p_1 and, consequently $E[R]$ in relation to a certain flood hazard variable is not as simple to define as in the case of a simple threshold. On the one hand, in our knowledge, no studies have been carried out on this topic (at least in the flood damage modelling field), and on the other, an expert-based definition of a complete fragility curve is not a straightforward task. It is, however, possible to define reasonable lower and upper thresholds for the distribution of p_1, below which one can be reasonably sure that the probability of damage is close to 0 and above which it is approximately 1. This is the adopted approach in the model, in which a normal distribution of the probability was considered between the two values.

For example, in INSYDE, internal plaster is considered to be removed and replaced when at least one of the following conditions occurs:

- Long duration flood (d>12 hours): longer residence time enhances water penetration into the plaster. The expected damage ratio E[R] is given by the distribution shown in Figure 1.

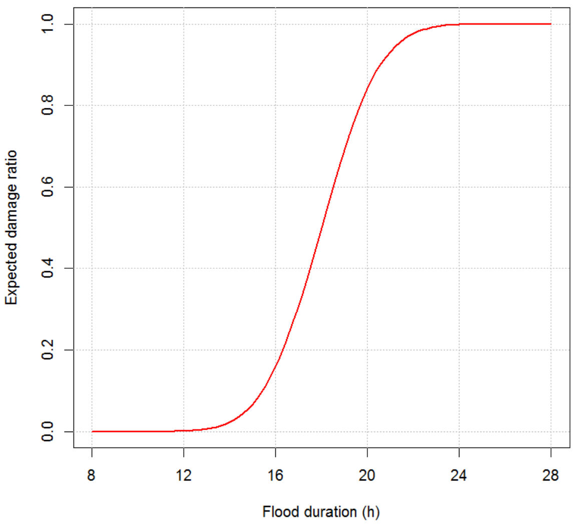

Figure 1. Distribution of the expected damage ratio to internal plaster in function of the flood duration.

- Presence of contaminants (q=1): plaster replacement is usually required in case of contaminated water. In such scenarios, the expected damage ratio E[R] is 1.
- Level of maintenance is “average” or poor”, which implies a more vulnerable plaster, even under short duration floods and/or absence of contaminants in the water. For those building maintenance levels, E[R] is considered to be 1.

If more than one of the conditions mentioned above occur, E[R] is considered the maximum among the three. The underlying assumption is that the most unfavourable condition dominates the damage mechanism, independently of the others. As an example, if a flood with a duration of 20 hours occurs, in which the water contains contaminants, and a building with the high level of maintenance is affected, the expected damage ratio for its internal plaster would be given by:

$$E[R] = \max(0.84; 1; 0) = 1 \quad (7)$$

The quantity of damaged plaster is considered to depend on external water depth, incremented by 1.00 m in order to account for capillary rise:

$$extension = (h + 1.00) \cdot IP \qquad [\mathrm{m}^2] \quad (8)$$

where h is the internal water depth and IP is the internal perimeter of the building.

In addition to expert knowledge and technical papers, the setup of the damage functions was supported by an observational method which helped to identify the most influencing variables on damage occurrence for the different building subcomponents. In particular, an analysis has been carried out on the relation between observed damages and the damage explicative parameters (hazard and vulnerability parameters) considered by INSYDE, using high detailed damage data for about 60 affected buildings during the November 2012 flood in the Umbria Region, Central Italy (Molinari et al., 2014). Chi-square hypothesis tests were performed on contingency tables based on available data, in order to analyse the possibility of any correlation between certain *Event* and *Building* variables and damage mechanisms on building elements. A higher correlation was found for water depth, in particular for the electrical system (significance level α=0.01), windows (α=0.05), clean-up and plumbing system (α=0.05). Duration and water quality seemed to be less significant on damage occurrence for most of the building components, except for exterior plaster (duration, α=0.10 and water quality, α=0.05), pavement (duration, α=0. 05) and clean up (water quality, α=0.10). With respect to *Building* variables, a higher correlation was found for the presence of basement, in particular for the electrical system (α=0.01) and interior plaster (α=0.05).

The outcome of the analysis was integrated with loss adjustment evaluations in recent flood events in Emilia-Romagna Region (Northern Italy), and the results have been used to corroborate the dependencies adopted in damage functions. Figure 2 provides an example of the damage functions developed for a default building in the case of a long duration (d=48 hours), high-velocity flood (v=2.5 m/s), with presence of pollutants (q=1) and a sediment concentration s=0.05.

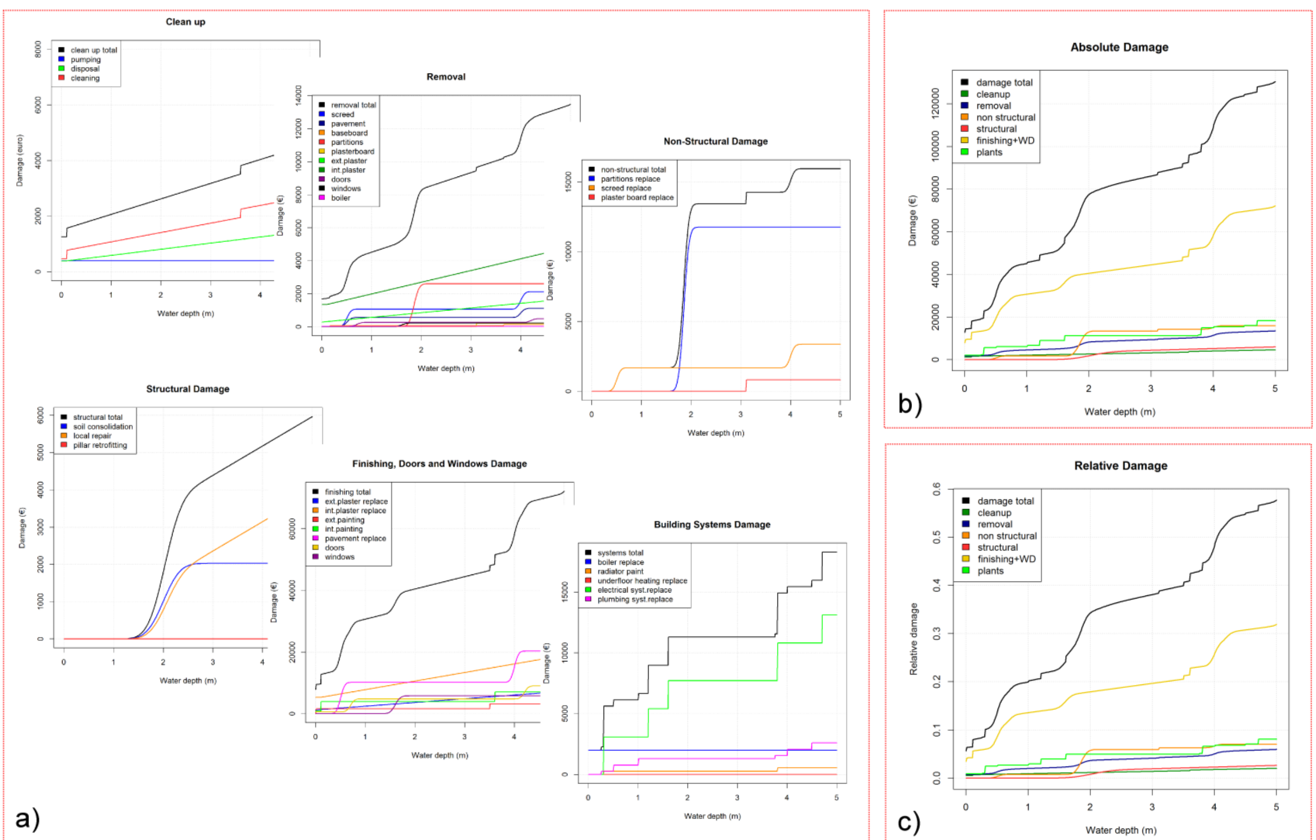

Figure 2. Example of INSYDE damage functions (considering the following Event variables: flow velocity = 2.5 m/s, flood duration = 48 hours, sediment concentration = 0.05, water quality = presence of pollutants): a) Different building subcomponents; b) Absolute damage functions for total damage and different building components; c) Relative damage functions for total damage and different building components.

To complete the INSYDE methodology, the absolute damage figures computed can be converted into relative value by dividing them by the replacement value of the building. This value is given as a function of the building type and structure, based on existing literature and official studies (Cresme-Cineas-Ania, 2014).

3 Results and discussion

3.1 Model validation

The model was validated using the damage data of the 2010 flood collected by the municipality of Caldogno in Veneto Region, Northeast of Italy. Available building loss data, related to about 300 affected buildings, were based on the "Quantification of damage" forms sent out by the authorities, in the frame of the loss compensation process by the State. Damage data consisted in actual restoration costs, certified by original receipts and invoices. The total reported damage was estimated to be approximately 7.5 M€.

Besides registered losses, the following *Event* and *Building* information was available (Scorzini and Frank, 2015):

- external water depth (h_e) and flow velocity (v) at buildings' location, resulting from 1D-2D hydraulic modelling of the flood event;
- sediment load (s): fine-grained sediment, s=0.05;
- floor area (FA) and number of floors (NF) of damaged buildings;
- structural type of damaged buildings (BS): almost equally distributed among reinforced concrete and masonry buildings;
- typology of damaged buildings (BT): 151 detached houses, 70 semi-detached houses and 75 apartment buildings. A further distinction between elements with and without basement was available. In addition, a finishing level (FL) was attributed to each single building based on its quality;
- year of construction (YY) of the buildings.

INSYDE was applied on the case study with this data as input, while default values of Tables 2 and 3 were assumed for missing variables. Calculated total damage was equal to 7.42 million Euro, with a relative error of -1.7%.

Figure 3, showing estimated damages against observed ones, provides a more in depth analysis of the results. The model, while overestimating low entity damages, tended to underestimate high damages, with a root mean square error (RMSE) equal to 28'996 Euro.

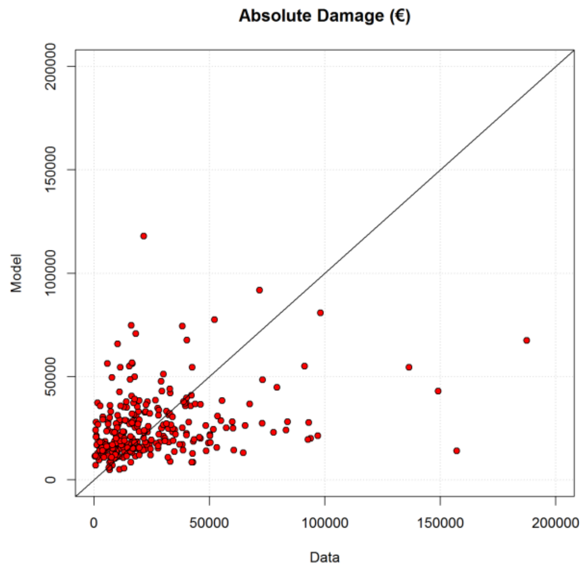

Figure 3. Scatter plot of observed against modelled damages for the buildings affected by the 2010 flood in Caldogno.

Given this dispersion in the data, the results were compared to those obtained with the application of other micro-scale damage functions from the literature on the same case study (Scorzini and Frank, 2015). These included: Debo (1982), Dutta et al. (2003), FLEMOps (Thieken et al., 2008) and others specifically applied in damage assessment studies in Italy, i.e. Oliveri and Santoro (2000), Luino et al. (2009) and Arrighi et al. (2013).

Table 4 summarises total damage estimates and RMSE calculated by using the selected micro-scale models and INSYDE. The output from these functions ranged from 5.8 to 13 million Euro, resulting in a maximum relative error from the reported building damage (7.5 million Euro) of about 73.6% (RMSE=34'990 Euro), obtained with the curve of Dutta et al. (2003). The others gave similar results, with relative errors in the order of 12-23% (RMSE ≈ 28'000-29'600 Euro), excluding the function of Luino et al. (2009), which overestimated damage by more than 45% (RMSE=30'230 Euro). The relative high value of the RMSE obtained from the application of the different models was mainly due to the intrinsic natural spread of damage data (Smith, 1994), which makes a perfect fit of a damage model practically impossible. From this perspective, INSYDE, supported by a physically based methodology, provided encouraging results, with a relatively small observed RMSE and the minimum relative error (-1.7%) on the total damage figure.

3.2 Sensitivity analysis

The damage dataset used to validate the model in Section 3.1 does not allow to fully investigate the model behaviour. The limited total flood extent and the slow flow processes occurred in the study area resulted in low values of hazard variables like flow velocity and sediment load. Therefore, the test did not allow to assess the influence of these parameters in determining the damage, that is, the sensitivity of the model structure to high values of velocity and sediment load. To further explore the importance of each hazard variable, we performed a local sensitivity analysis. In this application, the damage is computed by varying alternatively each hazard parameter while the others are kept constant. The exposure and vulnerability variables have not been considered at this stage.

Two different flood conditions have been considered to explore the model behaviour in different conditions: a low velocity, long duration flood and conversely a high velocity, short duration flood event. For the first case, the fixed values of depth, velocity, duration and sediment load are respectively h=1.5 m, v=1.0 m/s, d=18 h and s=0.10. For the second, the values are h=2.0 m, v=2.0 m/s, d=8 h and s=0.10.

Computations are performed considering a standard reinforced concrete building with 2 floors and a basement, 100m^2 of floor area and high finishing level. The other building characteristics are set using the previously mentioned default values.

Figures 4 and 5 summarise the results of the local sensitivity analysis in the two chosen flood conditions, showing the relative influence of each hazard variable in determining the total damage. As expected, water depth is the most influential parameter, since all the damage functions directly depend on it. Relative changes in flood duration have much more impact in low velocity, long duration events, while the relevance of velocity is more evident at higher values, when structural damages can become important. In both scenarios, sediment load has a relatively marginal importance. The influence of water quality was not included in Figures 4 and 5 because it is a binary variable and, therefore, cannot be increased or decreased incrementally and directly compared with the other variables. Both base cases were thus computed considering absence of pollutants. To illustrate the influence of this hazard variable on model results, we computed the same two base cases separately, considering presence of pollutants. The relative increase in damage ranges from around 30% to 45%.

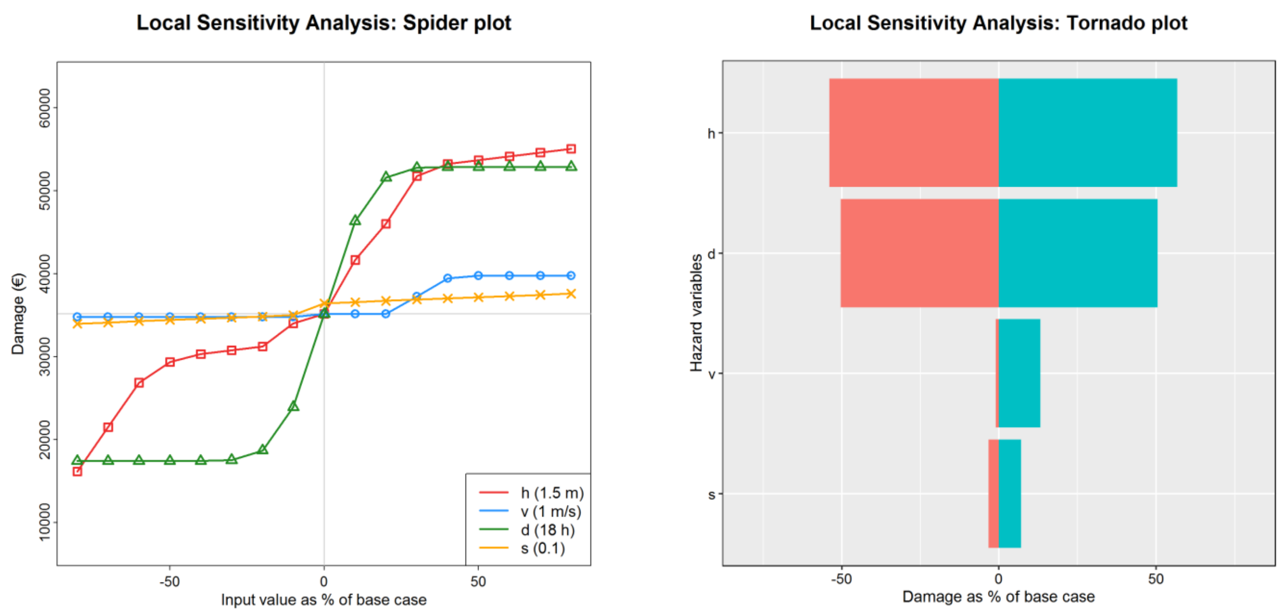

Figure 4. Results of the local sensitivity analysis in case of low velocity, long duration flood.

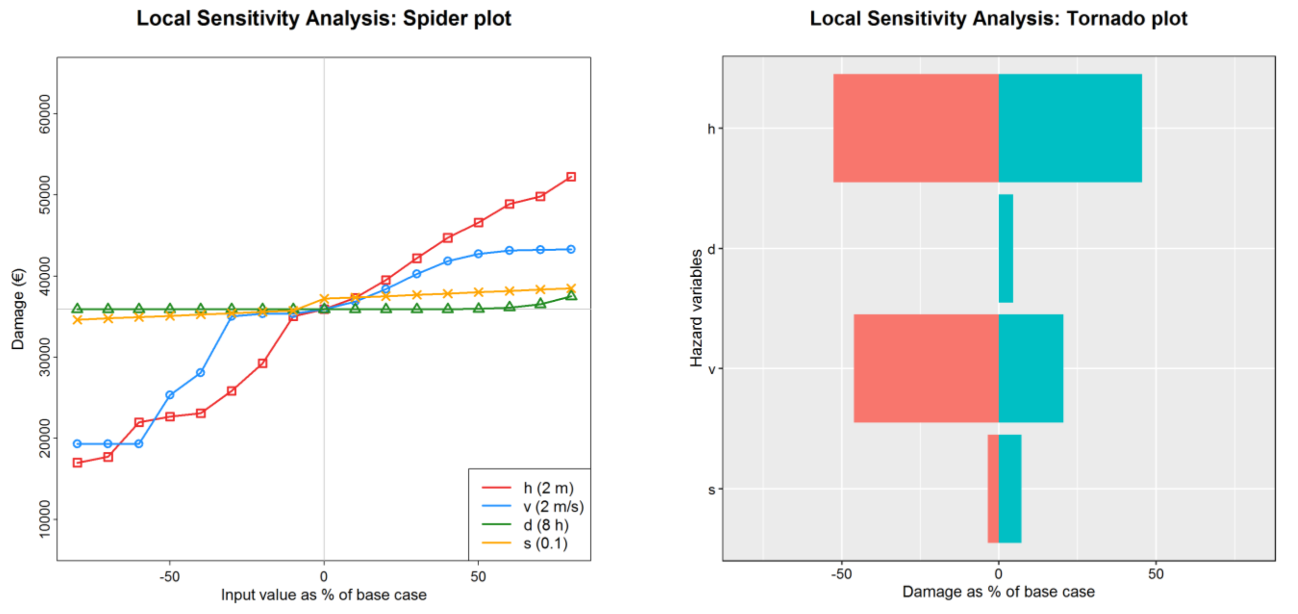

Figure 5. Results of the local sensitivity analysis in case of high velocity, short duration flood.

3.3 Critical analysis of the model

The approach followed in INSYDE was derived from a detailed analysis of the present state of art of synthetic flood damage modelling for the residential sector, as depicted in Table 5. The table reports, for the main models found in the literature: considered hazard and vulnerability parameters, the estimated types of damage, the approach for the monetary evaluation of damage, whether or not models have been validated and whether or not a sensitivity analysis has been performed. Starting from this analysis, the main strengths of existing models have been identified and incorporated in INSYDE. Likewise, INSYDE tries to overcome the limitations of available approaches.

As far as hazard and vulnerability are concerned, similarly to the model developed within the FloodPROBE project (Walliman et al., 2013), INSYDE allows considering all the hazard parameters which were found as significant in the literature, namely water depth, velocity, sediment and contaminant loads, and flood duration (Kelman and Spence, 2004; Thieken et al., 2005; Kreibich et al., 2009; Merz et al., 2010). Moreover, the vulnerability features of any specific building can be defined by means of a set of parameters (such as building size, type, structure, finishing level, maintenance level, etc.), allowing for an in-depth analysis of vulnerability (see the FloodPROBE and the MCM models). This overcomes the problem of the representativeness of the entire building stock by means of a set of predefined building types, presently characterizing the majority of models. On the other hand, some of the information required by the model may not always be available. For this reason, default value are included for all model parameters, based on the most observed common values (Table 2).

As regards estimated damages, INSYDE presents two main strengths. First, likewise the FloodPROBE and MCM (Penning-Rowsell et al., 2005) models, damage functions are derived component by component allowing an in-depth analysis/description of damage mechanisms (Section 2). Second, not only damage to the building fabric and functions (e.g. systems) are modelled, but also costs related to the cleaning of the building, the removal of water and waste as well as of drying, which can represent an important share of the total damage. Damage to inventories is not considered at the moment, as inventories present a higher variability than the building fabric, requiring a mixed empirical-synthetic approach. However, a future extension of the model has been already planned. It is also important to note that, in the current version, the model considers only the potential damage, while factors that can affect damage, such as flood warning, preparedness and precautionary measures, were not incorporated. Additional corrective coefficients should be used in order to adjust potential to actual losses (Smith, 1994; Thieken et al., 2005; Messner and Meyer, 2006; Poussin et al., 2015).

Regarding the monetary estimation of damage, INSYDE first estimates damages in physical terms. This is an important feature, as physical measures are undisputable, while associated monetary values depend on the estimation method, underlying assumptions, stakeholders, etc. The analysis of damage in physical units supplies unambiguous estimates that can be used as the base for different economic evaluations. In INSYDE, the monetary translation is carried out subsequently, by using building price books that can be updated and adapted to the region of implementation of the model. This way, the model can be easily applied to different geographical regions.

Another important feature of INSYDE regards the treatment of uncertainty embodied in the model structure. The contribution of hazard components of risk to total damage uncertainty has been highlighted in several research works, considering the uncertainty related to damage models (Merz and Thieken, 2009; Merz et al., 2010, de Moel and Aerts, 2011, Thieken et al., 2014), or comparing the results of various damage models or curves (Apel et al., 2008; Jongman et al., 2012; De Moel and Aerts, 2011; Schröter et al., 2014). Relatively few works performed a comprehensive sensitivity analysis of damage estimations to different sources of uncertainty, or presented methods to explicitly account for it in applications. Egorova et al. (2008) assessed uncertainties in the value of elements at risk and developed a methodology to incorporate uncertainties in depth–damage curves. De Moel and Aerts (2011) evaluated the influence of several factors on damage estimates, and they concluded that the uncertainty coming from the determination of values of elements at risk and the choice of a damage model is much more influent than other sources like land use data and inundation maps. Schröter et al. (2014) applied eight flood damage models with different levels of complexity to predict relative building damage in residential sector for five historic flood events in Germany. The authors observed that the use of additional explanatory variables besides the water depth improved models’ predictive capability especially in applications to different regions and different flood events. In addition, models based on probabilistic structure (e.g. Bayesian networks) resulted more reliable than deterministic models.

In such a context, the main findings from the literature were taken into account in the development of the INSYDE model structure and respective R program, which enable the explicit analysis of model uncertainty by randomly sampling input parameters from distributions rather than single values, generating output damage distributions. An in-depth analysis of model sensitivity and uncertainty is planned as a follow-up to the present research work. In this paper, we have included a local sensitivity analysis of individual hazard values, which serve not only to illustrate the potential of the model in this field, but also to calibrate and to perform a “sanity check” of model results.

On the other hand, it is the first time that uncertainty in damage mechanisms is included in a synthetic damage model. From this point of view, the probabilistic approach adopted in the model represents an innovation with respect to the present state of art.

4 Conclusions

In this paper, we presented a new synthetic damage model called INSYDE. The model incorporates the latest developments in flood damage modelling and has been designed to be a flexible and transparent methodology, suitable for a variety of applications regarding damage assessment, vulnerability analysis of buildings and analysis of uncertainty sources.

Model validation in a test case in Italy has shown that INSYDE can provide good estimates of post-event flood damages, with performances comparable or superior to most damage models available in the literature. In particular, the probabilistic approach used to derive the damage functions is key to correctly undertake the uncertainty issues regarding the model damage mechanisms and parameters.

Despite having been developed and tested with Italian case studies, the flexibility of the model structures allows to easily modify both the model structure (i.e. damage functions) and the model parameters (such as building characteristics and unitary prices) for application in other countries. For the same reason, the structure of INSYDE makes it adaptable, with appropriate modifications, for flood damage assessment to other sectors, such as building contents and commercial or industrial assets and agriculture.

In order to increase the transparency and reproducibility of the methodology, the development of a dedicated website for INSYDE. Thanks to a simple and user-friendly interface, users will have the possibility of applying the model to compute flood damage for the building type of interest and for any reference flood scenario. Furthermore, the model functions will be available for download as an R open source code. This way, the model can be also customized as users can change the value of model parameters, the shape of the different damage functions as well as reference prices for the monetary evaluation of damage. We believe that the use of open-access, transparent damage models can greatly contribute to improve the existing vulnerability models, and help vulnerability assessment studies in areas where few datasets and models are available.

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References

Andrè, C., Monfort, D., Bouzit. M., and Vinchon, C.: Contribution of insurance data to cost assessment of coastal flood damage to residential buildings: insights gained from Johanna (2008) and Xynthia (2010) storm events. Nat. Hazards Earth Syst. Sci., 13, 2003-2012, 2013. doi: 10.5194/nhess-13-2003-2013.

Apel, H., Merz, B., and Thieken, A.H.: Quantification of uncertainties in flood risk assessments, Int. J. River Basin Management, 6(2), 149-162, 2008. doi: 10.1080/15715124.2008.9635344.

Arrighi, C., Brugioni, M., Castelli, F., Franceschini, S., and Mazzanti, B.: Urban micro-scale flood risk estimation with parsimonious hydraulic modelling and census data. Nat. Hazards Earth Syst. Sci., 13, 1375–1391, 2013. doi:10.5194/nhess-13-1375-2013.

Bouwer, L.M., Papyrakis, E., Poussin, J., Pfurtscheller, C., and Thieken, A.H.: The Costing of Measures for Natural Hazard Mitigation in Europe. Nat. Hazards Rev., 15(4), 04014010, 2013. doi: 10.1061/(ASCE)NH.1527-6996.0000133.

Bubeck, P. and Kreibich, H.: Natural Hazards: direct costs and losses due to the disruption of production processes. CONHAZ Report WP1, D1.2, 2011.

Cresme-Cineas-Ania: Definizione dei costi di (ri)costruzione nell'edilizia. Eds. Cineas, 2014.

Debo, T.N.: Urban flood damage estimation curves. J. Hydraul. Div., 108(10), 1059–1069, 1982.

de Moel, H. and Aerts, J.C.J.H.: Effect of uncertainty in land use, damage models and inundation depth on flood damage estimates. Nat Hazards, 58, 407–425, 2011. doi: 10.1007/s11069-010-9675-6.

Dutta, D., Herath, S., and Musiake, K.: A mathematical model for flood loss estimation, J. Hydrol., 277, 24–49, 2003. doi:10.1016/S0022-1694(03)00084-2.

Egorova, R., Van Noortwuk, J.M., and Holterman, S.R.: Uncertainty in flood damage estimation. Int. J. River Basin Management, 6(2), 139–148, 2008. doi: 10.1080/15715124.2008.9635343.

Gersonius, B., Zevenbergen, C., Puyan, N., and Billah, M.M.M.: Efficiency of private flood proofing of new buildings-adapted redevelopment of a floodplain in the Netherlands. WIT Transactions on Ecology and the Environment, 118, 247-259, 2008. doi: 102495/FRIAR080241.

Handmer, J.: The chimera of precision: Inherent uncertainties in disaster loss assessment. Australian Journal of Emergency Management, 18(2), 88-97, 2003.

Jongman, B., Kreibich, H., Apel, H., Barredo, J.I., Bates, P.D., Feyen, L., Gericke, A., Neal, J., Aerts, J.C.J.H and Ward, P.J.: Comparative flood damage model assessment: towards a European approach. Nat. Hazards Earth Syst. Sci., 12, 3733–3752, 2012. doi:10.5194/nhess-12-3733-2012.

Kelman, I. and Spence, R.: An overview of flood actions on buildings. Eng Geol., 73 (3-4), 297-309, 2004. doi:10.1016/j.enggeo.2004.01.010.

Kreibich, H., Piroth, K., Seifert, I., Maiwald, H., Kunert, U., Schwarze, J., Merz, B., and Thieken, A.H.: Is flow velocity a significant parameter in flood damage modelling? Nat. Hazards Earth Syst. Sci., 9, 1679–1692, 2009. doi:10.5194/nhess-9-1679-2009.

Luino, F., Bidoccu, M., Cirio, C.G., Agangi, A., Giulietto, W., Godone, F., and Nigrelli, G.: Application of a model to the evaluation of flood damage, Geoinformatica, 13, 339–353, 2009. doi: 10.1007/s10707-008-0070-3.

Merz, B. and Thieken, A.H.: Flood risk curves and uncertainty bounds. Nat Hazards, 51(3), 437–458, 2009. doi: 10.1007/s11069-009-9452-6.

Merz, B., Kreibich, H., Schwarze, R., and Thieken, A.: Assessment of flood economic damage. Nat. Hazards Earth Syst. Sci., 10, 1697-1724, 2010. doi:10.5194/nhess-10-1697-2010.

Messner, F. and Meyer, V.: Flood damage, vulnerability and risk perception: challenges for flood damage research. In: Flood Risk Management: Hazards, Vulnerability and Mitigation Measures, 149–167. J. Schanze et al. (eds.), Springer. 2006. doi: 10.1007/978-1-4020-4598-1_13.

Messner, F., Penning-Rowsell, E., Green, C., Meyer, V., Tunstall, S., and van der Veen, A.: Evaluating Flood damages: guidance and recommendations on principles and methods, FLOODsite Report Number T09-06-01, 2007.

Meyer, V., Becker, N., Markantonis, V., Schwarze, R., Van den Bergh, J. C. J. M., Bouwer, L. M., ... and Hallegatte, S.: Assessing the costs of natural hazards-state of the art and knowledge gaps. Nat. Hazards Earth Syst. Sci., 13(5), 1351-1373, 2013. doi:10.5194/nhess-13-1351-2013.

Molinari, D., Menoni, S., Aronica, G.T., Ballio, F., Berni, N., Pandolfo, C., Stelluti, M. and Minucci, G.: Ex post damage assessment: an Italian experience. Nat. Hazards Earth Syst. Sci., 14(4), 901-916, 2014. doi:10.5194/nhess-14-901-2014.

Nadal, N.C., Zapata, R.E., Pagàn, I., Lopez, R., and Agudelo, J.: Building damage due to riverine and coastal floods. J. Water Resour. Plann. and Manage., 136(3), 327-336, 2010. doi: 10.1061/(ASCE)WR.1943-5452.0000036 .

Neubert, M., Naumann, T., Hennersdorf, J., and Nikolowski J.: The Geographic Information System-based flood damage simulation model HOWAD. Journal of Flood Risk Management, 9(1), 36-49, 2016. doi: 10.1111/jfr3.12109.

Oliveri, E. and Santoro, M.: Estimation of urban structural flood damages: the case study of Palermo. Urban Water, 2, 223-234, 2000. doi:10.1016/S1462-0758(00)00062-5.

Penning-Rowsell, E., Johnson, C., Tunstall, S., Tapsell, S., Morris, J., Chatterton, J., and Green, C.: The benefits of flood and coastal risk management: a handbook of assessment techniques. Middlesex University Press, UK, 2005.

Poussin, J. K., Botzen, W.W., and Aerts, J.C.: Effectiveness of flood damage mitigation measures: Empirical evidence from French flood disasters. Global Environmental Change, 31, 74-84, 2015. doi:10.1016/j.gloenvcha.2014.12.007.

Rossetto, T. and Elnashai, A.: Derivation of vulnerability functions for European-type RC structures based on observational data. Engineering Structures, 25(10), 1241-1263, 2003. doi:10.1016/S0141-0296(03)00060-9.

Rota, M., Penna, A., and Strobbia, C.L.: Processing Italian damage data to derive typological fragility curves. Soil Dynamics and Earthquake Engineering, 28, 933-947, 2008. doi: 10.1016/j.soildyn.2007.10.010.

Schröter, K., Kreibich, H., Vogel, K., Riggelsen, C., Scherbaum, F., and Merz, B.: How useful are complex flood damage models? Water Resour. Res., 50(4), 3378-3395, 2014. doi: 10.1002/2013WR014396.

Scorzini, A.R. and Frank, E.: Flood damage curves: new insights from the 2010 flood in Veneto, Italy. Journal of Flood Risk Management, 2015. doi: 10.1111/jfr3.12163.

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

Thieken, A.H., Müller, M., Kreibich, H., and Merz, B.: Flood damage and influencing factors: New insights from the August 2002 flood in Germany. Water Resour. Res., 41(12), W12430, 2005. doi:10.1029/2005WR004177.

Thieken, A.H., Olschewski, A., Kreibich, H., Kobsch, S. and Merz, B.: Development and evaluation of FLEMOps – a new flood loss estimation MOdel for the private sector. In: D. Proverbs, C.A. Brebbia & E. Penning-Rowsell, eds. Flood recovery, innovation and response, 315–324, WIT Press, Southampton, UK. 2008.

Thieken, A.H., Apel, H., and Merz, B.: Assessing the probability of large-scale flood loss events: a case study for the river Rhine, Germany. Journal of Flood Risk Management, 8(3), 247-262, 2014. DOI: 10.1111/jfr3.12091.

Velasco, M., Cabello, A., and Russo, B.: Flood damage assessment in urban areas. Application to the Raval district of Barcelona using synthetic depth damage curves. Urban Water Journal, 13(4), 426-440, 2016. doi: 10.1080/1573062X.2014.994005.

Walliman, N., Baiche, B., Odgen, R., Tagg, A., Escarameia, M.: Estimation of repair costs of individual non-domestic buildings damaged by floods. Int. J. of Safety and Security Eng., 3(4), 289-305, 2013. doi: 10.2495/SAFE-V0-N0-1-16.

Damage components		Event features						Building characteristics																
		External water depth (he)	Internal water depth (h)	Flow velocity (v)	Sediment load (s)	Duration (d)	Water quality (q)	Internal area (IA)	Basement area (BA)	External perimeter (EP)	Internal perimeter (IP)	Basement perimeter (BP)	Number of floors (NF)	Interfloor height (IH)	Basement height (BH)	Ground floor level (GL)	Basement level (BL)	Building type (BT)	Building structure (BS)	Finishing level (FL)	Level of maintenance (LM)	Year of construction (YY)	Heat. syst. distribution (PD)	Heat. syst. type (PT)
Clean-up	C1 - Pumping							x	x							x	x	x						
	C2 - Waste disposal		x		x		x	x	x						x			x						
	C3 - Cleaning		x				x	x	x		x	x		x	x			x						
	C4 -Dehumidification		x			x		x	x					x	x			x						
Removal	R1 - Screed		x			x		x						x				x		x				
	R2 - Pavement		x			x		x						x				x		x				
	R3 - Baseboard		x			x					x			x				x						
	R4 - Partition walls		x			x					x			x				x	x					
	R5 - Plasterboard		x					x						x				x		x				
	R6 - External plaster	x		x		x	x			x								x			x			
	R7 - Internal plaster		x			x	x				x	x			x			x			x			
	R8 - Doors		x	x		x		x	x					x				x						
	R9 - Windows		x	x		x		x						x				x						
	R10 - Boiler		x					x	x					x				x					x	
Non structural	N1 - Partitions replacement		x			x					x			x				x	x					
	N2 - Screed replacement		x			x		x						x				x		x				
	N3 - Plasterboard replacement		x					x						x				x		x				
Structural	S1 - Soil consolidation	x		x				x					x	x				x	x					
	S2 - Local repair	x		x	x					x								x	x					
	S3 - Pillar repair	x		x	x					x								x	x					
Finishing	F1 - External plaster replace.	x		x		x	x			x								x			x			
	F2 - Internal plaster replace.		x			x	x				x	x			x			x			x			
	F3 - External painting	x								x				x				x		x				
	F4 - Internal painting		x								x	x		x	x			x		x				
	F5 - Pavement replacement		x			x		x						x				x		x				
	F6 - Baseboard replacement		x			x					x			x				x						
Windows & Doors	W1 - Doors replacement		x	x		x		x	x					x				x		x				
	W2 - Windows replacement		x	x		x		x						x				x		x				
Building Systems	P1 - Boiler replacement		x					x	x					x				x					x	

		P2 - Radiator painting	x				x	x	x		x
		P3 - Underfl. heating replace.	x		x		x	x	x	x	x
		P4 - Electrical syst. replace.	x				x	x	x	x	
		P5- Plumbing syst. replace.	x	x		x	x	x	x	x	

Table 1: Damage components and subcomponents considered in INSYDE, and relationships with *Event features* and *Building characteristics* parameters.

Variable	Description	Unit of measurement	Range of values	Default values
he	Water depth outside the building	m	≥ 0	[0;5] Incremental step: 0.01 m
h	Water depth inside the building (for each floor)	m	[0;IH]	h=f(he,GL)
v	Maximum velocity of the water perpendicularly to the building	m/s	≥ 0	0.5
s	Sediment load	% on the water volume	[0;1]	0.05
d	Duration of the flood event	hours	> 0	24
q	Water quality (presence of pollutants)	-	0: No 1: Yes	1

Table 2: *Event features* parameters considered in INSYDE.

Variable	Description	Unit of measurement	Range of values	Default values
FA	Footprint area	m^2	> 0	100
IA	Internal area	m^2	> 0	0.9·FA
BA	Basement area	m^2	≥ 0	0.5·FA
EP	External perimeter	m	> 0	$4\cdot\sqrt{FA}$
IP	Internal perimeter	m	> 0	2.5·EP
BP	Basement perimeter	m	> 0	$4\cdot\sqrt{BA}$
NF	Number of floors	-	≥ 1	2
IH	Interfloor height	m	> 0	3.5
BH	Basement height	m	> 0	3.2
GL	Ground floor level	m	[-IH; > 0]	0.1
BL	Basement level	m	< 0	-GL-BH-0.3
BT	Building type	-	1: Detached house 2: Semi-detached house 3: Apartment house	1
BS	Building structure	-	1: Reinforced concrete 2: Masonry	2
FL	Finishing level (i.e. building quality)	-	0.8: low 1: medium 1.2: high	1.2
LM	Level of maintenance	-	0.9 : low 1: medium 1.1: high	1.1
YY	Year of construction	-	≥ 0	1994
PD	Heating system distribution	-	1: centralised 2: distributed	1 if YY≤1990 2 otherwise
PT	Heating system type	-	1: radiator 2: pavement	2 if YY>2000 and FL>1 1 otherwise

Table 3: ***Building characteristics*** **parameters considered in INSYDE.**

	Debo	Dutta et al.	FLEMOps	Oliveri & Santoro	Luino et al.	Arrighi et al.	Insyde
Calculated damage [M€]	5.79	13.10	6.58	5.93	10.95	6.34	7.42
Relative error [%]	-23.3	+73.6	-12.8	-21.4	+45.2	-16.0	-1.7
RMSE [€]	28’302	34’990	28’116	27’972	30’230	29’622	28’996

Table 4: Comparison of the damage estimates produced by INSYDE and other literature models.

Model or Authors	Hazard parameters	Vulnerability parameters	Type of damage considered	Monetary evaluation	Validation	Sensitivity analysis	Weaknesses	Strengths
Oliveri and Santoro (2000)	Water depth	Two typical buildings classified according to: - number of storey - finishing level	- Building fabric and systems - Building inventory - Dismantling costs of building components	Building price books	No	No	- Only two building types are considered - No explicit analysis of damage to different building components - Not validated	
Multi Coloured Manual (MCM) (Penning-Rowsell et al., 2005)	Water depth Flood duration	140 typical buildings according to: - construction type - period of construction - social class of occupants	- Building fabric and systems - Building inventory - External areas (gardens, fences, sheds) - Clean-up costs	Building price books	No	No	Not validated	- Large building dataset - In-depth analysis of vulnerability - Possibility of analyzing damage on individual components
Gersonius et al. (2008)	Water depth Flow velocity	5 typical buildings according to: - construction type - ground floor area	- Partial collapse - Building fabric and systems - Clean-up and disinfection costs	- Past experience - Expert interviews	No	No	Not validated	
Nadal et al. (2010)	Water depth Flow velocity Debris content	28 typical buildings according to: - construction type - height of the building - floor area	- Building fabric - Building collapse - Building utilities and finishes -Local soil scour	Not specified	No	No	Not validated Monetary evaluation not explained	-Use of a probabilistic approach - Possibility of analysing damage on individual components
FloodProbe (Walliman et al. 2013)	Water depth Flow velocity Debris content Flood duration Contamination	Possibility of defining the specific features of the affected building	- Building fabric and systems - Clean-up costs - Drying costs	- Building price books - Databases used by quantity surveyors	Yes	Yes, only for hazard parameters	Huge amount of input variables (no default values)	-In-depth analysis of vulnerability -Adjustment factor for regional differences -Valid for non-residential building -Possibility of analysing damage on individual components

Velasco et al. (2016)	Water depth	1 typical building	- Building fabric and systems - Building inventory - Clean-up g costs - Water pumping costs	Past experience	Yes + calibrati on with past event	No	- Only one building type is considered - Only influence of water depth is considered	Embedded into a GIS tool
HOWAD (Neubert et al. 2016)	Water depth	12-14 typical buildings according to: - building material - construction type - design issues - period of construction	- Building fabric and systems - Building inventory - Drying costs	- Building price books - Expert interviews	Yes	No	Only influence of water depth is considered	Embedded into a GIS tool

Table 5: Review of existing synthetic damage models.