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

1 Introduction

Flood damage evaluation is a crucial component of any strategy for flood risk mitigation and management. In particular, models and methodologies for estimating economic damages are key for evaluating and comparing flood mitigation measures and for defining flood risk management plans. Synthetic models adopt a conceptual expert-based approach using hypotheses and assumptions about damage mechanisms (what-if analysis). Synthetic damage models can be employed for a variety of applications, such as the derivation of damage functions for different types of assets, post-event damage estimation, and analysis of uncertainty sources in damage assessments. Still, subjectivity in what-if analyses may result in uncertain damage estimates. In addition, these models are often affected by a lack of transparency, which limits their applicability, transferability, and improvements. Indeed, 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 well explained. 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 applicable to 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. Conversely, 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. The damage functions composing the model have been designed using an expert-based approach with the support of existing scientific and technical literature, loss adjustment studies, and damage surveys carried out for past flood events in Italy. Note: The version in this paper is limited to residential building damage estimation. 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 commercial or industrial buildings.

2 Model description

INSYDE adopts a synthetic approach consisting of 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 also be referred to as a what-if analysis. Damages are first modelled on a component-by-component basis using physically based mathematical functions and are then converted into monetary terms using full replacement costs derived from reference price lists. The overall economic damage to a building is obtained by summing each of the different damage components: clean-up and removal costs, structural damage, non-structural damage, damage to finishing elements, damage to windows and doors, and damage to building systems. 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: 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 that describe features and geometry of the building. Building features affect damage estimation either by modifying the functions describing damage mechanisms (e.g. system distribution, build- ing structure) or by affecting the unit prices of the building components by a certain factor (e.g. building type, finishing level). Conversely, 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. door removal cost per square metre, pavement replacement cost per square metre). The cost for each subcomponent is determined by the unit price (up) and the extension (ext). The latter 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. This distinction is useful for model generalization. The extension of the damage is determined only by the physical effects that the flood event causes to the building; therefore, the same approach can be applied in different countries or geographic areas, provided that the local characteristics of the buildings are accounted for. Unit prices, instead, vary from country to country or even within a country, they can also be referred to standard or default unit prices in official publications. Therefore, local price values are well identified and can be easily replaced with more suitable ones in this approach. Tables 1 and 2 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 variables listed in Tables 1 and 2 can directly affect damage estimation in terms of extension or indirectly by influencing other variables. An example of the latter case is YY (year of construction), which has no direct impact on the damage mechanisms of the different building subcomponents but indirectly influences the selection of other variables such as PD (heating system distribution) and PT (heating system type). Another example is NF (number of floors), which only directly affects soil consolidation despite indirectly influencing many other building components because damage on upper floors can only occur if the floors actually exist in the building. The number of flooded floors is then calculated as a function of inundation depth and interfloor height of the building (IH). It is important to underline that during the model design, observed damage data were essentially used to analyse the relations between hazard parameters and damage mechanisms in order to improve physical damage functions. For instance, the functions for structural damage found in literature were implemented in the model after some modifications, as they were not in line with the observed damages. Such a usage is consistent with an expert-based approach because observed data were first interpreted and then used to modify parts of the model structure rather than applied to calibrate the parameters of existing functions. Figure 3 provide an example of damage functions developed for a default building in the case of a flood with a duration d = 24 h, flow velocity v = 2.0 m/s, sediment concentration s = 0.05, and presence of pollutants (q = 1).

Table 1. Event features parameters considered in INSYDE.

Variable	Description	Unit of measurement	Range of values	Default values
h_e	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]	$h = f(h_e, \mathrm{GL})$
v	Maximum velocity of the water perpendicular to the building	$\mathrm{m\,s^{-1}}$	≥ 0	0.5
s	Sediment load	% on the water volume	[0; 1]	0.05
d	Duration of the flood event	h	> 0	24
q	Water quality (presence of pollutants)	–	0: No 1: Yes	1

Table 2. Building characteristics parameters considered in INSYDE.

Variable	Description	Unit of measurement	Range of values	Default values
FA	Footprint area	$\mathrm{m^2}$	> 0	100
IA	Internal area	$\mathrm{m^2}$	> 0	$0.9 \cdot \mathrm{FA}$
BA	Basement area	$\mathrm{m^2}$	≥ 0	$0.5 \cdot \mathrm{FA}$
EP	External perimeter	m	> 0	$4 \cdot \sqrt{\mathrm{FA}}$
IP	Internal perimeter	m	> 0	$2.5 \cdot \mathrm{EP}$
BP	Basement perimeter	m	> 0	$4 \cdot \sqrt{\mathrm{BA}}$
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	$[-\mathrm{IH}; > 0]$	0.1
BL	Basement level	m	< 0	$-\mathrm{GL} - \mathrm{BH} - 0.3$
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: centralized 2: distributed	1 if $\mathrm{YY} \leq 1990$ 2 otherwise
PT	Heating system type	–	1: radiator 2: pavement	2 if $\mathrm{YY} > 2000$ and $\mathrm{FL} > 1$ 1 otherwise

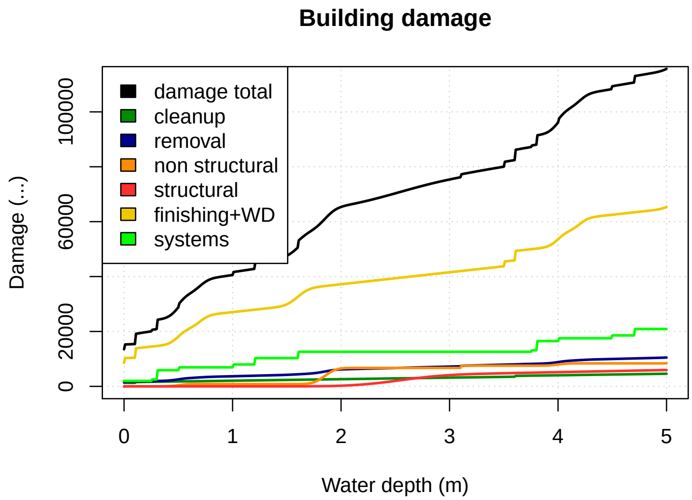

Figure 1. Example of INSYDE damage functions considering the following event variables: flow velocity = 2.0 m/s , flood duration = 24 h, sediment concentration = 0.05, and water quality = presence of pollutants (1=yes, 0=no). Damage functions for entire building and different building components.

3 Sensitivity analysis

To further explore the importance of each of these parameters (i.e. water depth, flow velocity, and sediment load), we performed a local sensitivity analysis. In this application, the damage was computed by varying alternately each hazard parameter while the others were kept constant. The building characteristics variables have not been analysed 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 were respectively h = 1.5 m, v = 1.0 m/s, d = 24 h and s = 0.10. For the second case, the values were h = 2.0 m, v = 2.0 m/s, d = 10 h and s = 0.10. Computations were performed considering a standard reinforced concrete building with two floors and a basement, 100mˆ2 of floor area, and a high finishing level. The other building characteristics were set using the previously mentioned default values. Figures 2 and 3 summarize 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 economic 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 q is not included in Figs. 2 and 3 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 the absence of pollutants (q = 0). To illustrate the influence of this hazard variable on model results, we

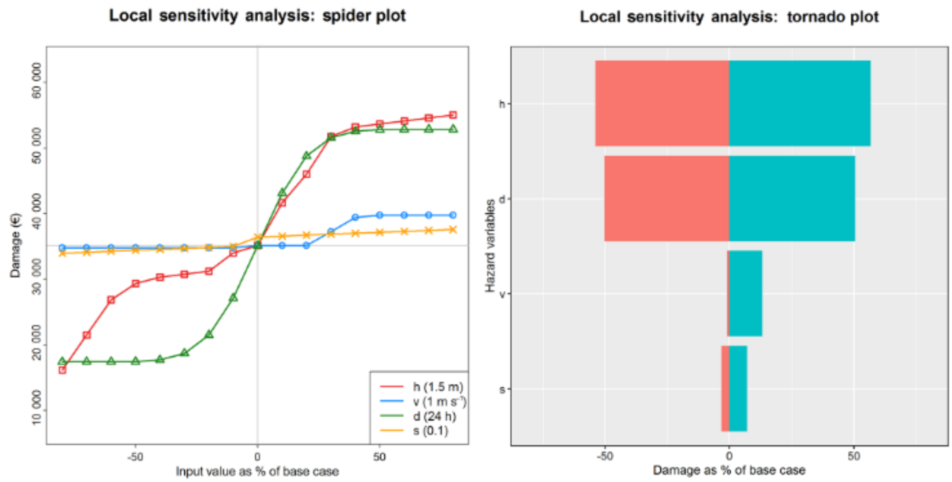

Figure 2. Results of the local sensitivity analysis in case of low velocity, long duration flood.

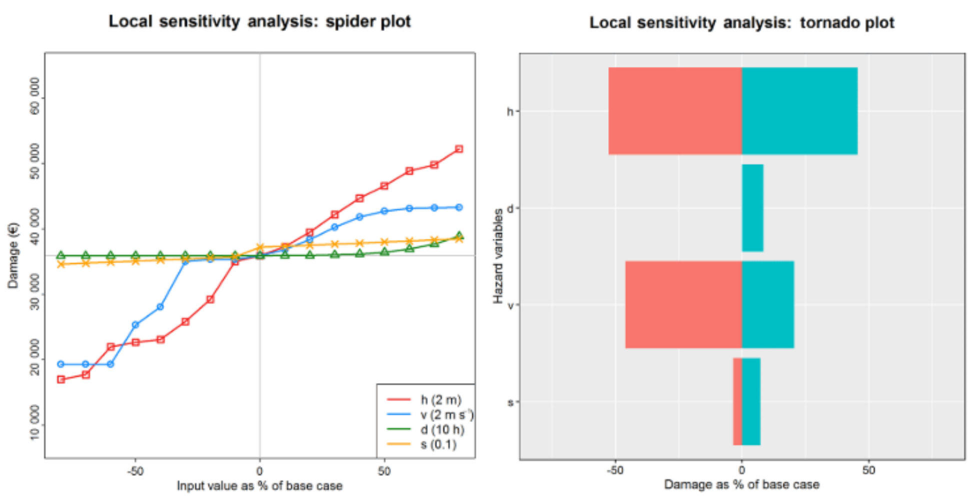

Figure 3. Results of the local sensitivity analysis in the case of high velocity, short duration flood.

computed the same two base cases separately considering the presence of pollutants (q = 1). The resulting relative increase in damage for the presence of pollutants ranges from around 30 to 45 %.

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