# A comparative analysis of flood damage models: lessons learnt and future challenges

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**Abstract.** Flood damage assessment is crucial to address the challenges of climate and socio-economic changes. Researchers and practitioners have developed several damage models to tackle local and regional situations. Particularly for direct damages to the residential sector, these models rely on numerous hypothesis (e.g. zero damage threshold) and parameters (e.g. recovery costs) assumed to fit specific local conditions and available data. Thus, transferability of damage models and reliability of observed losses have become key topics in the debate.This work aims at understanding the behaviour of different residential building damage models through their application to a case study in order to compare assumptions, estimated exposure values and losses. The research work is designed as a "blind" exercise where different research groups make a damage assessment starting from the same building dataset. Nine models are applied to estimate exposure and damage at the single-building scale. The results are compared in terms of exposure values, total damage and individual building damage. Although damage models differ in assumptions and parameters, the application highlights a good correlation among models in terms of exposure and relative damage, while correlation with monetary damage recorded in claims is low.

## 1 Introduction

The estimation of flood losses implies the use of vulnerability/exposure models for flood damage and risk assessment (Meyer et al. 2013; Zischg et al. 2018; Wagenaar et al. 2018; Molinari et al. 2019). According to Gerl et al. (2016), in central Europe there are 28 models with 652 functions to assess flood losses, whereas almost half of the functions refer to residential buildings. The main differences among damage models are: (i) spatial scale, (ii) metric (i.e. absolute or relative loss), (iii) exposure assessment (i.e. whole building or affected floors, market values or reconstruction-replacement costs), (iv) number of input variables, (v) calibration/validation with observed losses. These differences pose the issue of model transferability to other urban or environmental contexts.

With a joint effort of eight research groups, the objective of this study is to test and compare damage models for residential buildings used or developed by each group, by applying them in a "blind exercise", i.e. a common flood case study characterised by high availability of hazard and building data, with unknown information on observed losses in the implementation stage of the models.

As the research groups use approaches representing many different types and characteristics of models (e.g. univariable – multivariable; absolute – relative; graduated – regression – machine learning), being calibrated based

on empirical data stemming from different countries (Austria, France, Germany, Italy, Japan, Netherlands), with different landscapes, the blind exercise provides an extensive comparison of models and their transferability. The analysis of the differences in the ensemble of model outcomes aims at pointing out common patterns or divergent behaviours between model outcomes and with respect to observed losses.

## 2 Method

Nine damage models for residential buildings were selected for the study. They are shortly described below; further model details can be found in the respective references and in Molinari et al. (2020):

- the model by **Arrighi et al. (2018a, 2018b)** is a synthetic model which associates a relative physical damage to flood depth and then calculates a monetary damage as a function of the recovery cost (as a fraction of market value). The relative damage is calculated through two piece-wise linear stage-damage curves for buildings with and without basement. The model was created based on expert judgement for the city of Florence (Italy) and applied both at building and census block scale (Arrighi et al. 2018a, 2018b)

- The model developed by **CEPRI** (European Center for Flood Risk Prevention) is a synthetic multi-variable model expressing absolute damage as the expected sum of the actions required after a flood to go back to the pre-flood state. Water depth, submersion duration and building characteristics are considered (CEPRI, 2014a, b; Richert & Grelot, 2018).

- The model by **Dutta et al.** (2003) is a simple model considering flood depth only. The model supplies a relative damage, i.e. the degree of loss that describes the ratio of loss to the replacement value of the whole building; basement, number of exposed floors or other exposure variables are not separate inputs for the model, but are part of its variance.

- **FLEMOps** (Flood Loss Estimation MOdel for the private household sector) is a multi-variable, rule-based model estimating relative monetary flood loss to residential buildings as a function of water depth, building type and building quality, whereby it is not further differentiated between flooded floors, and the (non-)existence of a basement is not considered (Thieken et al. 2008). The model is empirically derived from data collected from 1697 households affected by the severe flooding of the rivers Elbe, Danube and some of their tributaries in August 2002 in Germany.

- The model by **Fuchs et al.** (2019) is a simple model considering flow depth only. It is a function developed for mountain areas, i.e. referring to house building tradition of the Alps and flood processes with sediment transport. The model supplies a relative damage, i.e. the degree of loss that describes the ratio of loss to the replacement value of the whole building.

- **INSYDE** (Dottori et al., 2016, Molinari et al. 2017) is an expert-based synthetic model developed for the Italian context. INSYDE adopts 23 input variables, six describing the flood event and 17 referring to building features. The model supplies damage in absolute terms by considering the replacement/recovery value of damaged components, and by referring only to flooded floors (including basement, if present). It was validated for different Italian flood events (Dottori et al., 2016; Molinari et al. 2017; Amadio et al. 2019).

- The model by **Jonkman et al.** (2008) is a simple model considering flow depth as the only explicative variable, calibrated on loss data in the Netherlands. As for Dutta et al. (2003) and Fuchs et al. (2019), the model supplies damage in relative terms.

- **Carisi_MV** (Carisi et al. 2018) is an empirical multi-variable model based on random forest approach, which estimates relative building losses considering six explicative variables: maximum water depth, maximum flow velocity, flood duration, monetary building value per unit area (based on market value), structural typology and footprint area of each building (Carisi et al. 2018). Calibration data come from a real inundation event by the Secchia river, in the province of Modena (Italy) in 2014. The model does not consider damages to basements.

- **Carisi_sqrtmono** (Carisi et al. 2018) is an empirical uni-variable model, calibrated on the previously cited 2014 Secchia flood event. The model supplies the relative damage to the building (using the market value to relativize the observed monetary damage), as a function of the maximum water depth h (m). The model doesn't consider basements or garages, for coherence with the calibration context.

The above models have been applied starting from common data available in the study area (see sect. 3). The results have been compared first among models and then versus the observed losses.

## 3 Case study

The study area is the town of Lodi (Italy), which in November 2002 was hit by a flood, caused by the overflow of the Adda River, which caused severe losses to buildings and economic activities. The event was chosen as reference for the exercise because it is well documented and hazard, exposure and vulnerability data are available. A 2D hydraulic reconstruction of the event is also available

(Scorzini et al. 2018), as well as micro-scale information on exposure and vulnerability of residential buildings.

Observed damage is known for 345 of the 877 flooded buildings, as derived from claims compiled by citizens after the occurrence of the flood, to ask for public compensation. Claim data have been stored in a georeferenced database by a team of researchers of Politecnico di Milano including information on the owner, the address of the flooded building, its typology (e.g. apartment, single house), the number of affected floors, a description of the physical damage and its translation in monetary terms (distinguishing, for the different rooms the building is made of, among damage to walls, windows and doors, floor, systems and content).

## 4 Results and discussion

In order to identify commonalities and dissimilarities among the different flood damage models, first, exposure estimates were compared, and, second, estimated losses have been compared to observed losses.

Table 1 shows the Pearson correlation coefficient for the estimated exposure. Although there are 9 models, exposure assessment can be common to different approaches, e.g. the models by Dutta et al. (2003), Fuchs et al. (2019), Jonkman et al. (2008). Table 1 shows very high correlation coefficients, meaning that all models start with a very similar approach for exposure assessment, although models have been developed for different contexts and different available data.

| | Arrighi et al. | Dutta, Fuchs Jonkman | FLEMO-ps | INSYDE | Carisi sqrtmono & MV |
|---|---|---|---|---|---|
| **Arrighi et al.** | 1 | 0.87 | 0.96 | 0.97 | 0.98 |
| **Dutta, Fuchs, Jonkman** | | 1 | 0.94 | 0.91 | 0.92 |
| **FLEMO-ps** | | | 1 | 0.99 | 0.99 |
| **INSYDE** | | | | 1 | 0.98 |
| **Carisi sqrtmono & MV)** | | | | | 1 |

**Table 1.** Pearson correlation coefficient for exposure estimates supplied by the models.

Less correlation is observed in monetary losses, since modelling approaches have several assumptions and differ in the shape of the damage functions and in the number of representative variables. For more details please refer to Molinari et al. (2020).

Table 2 shows a comparison between observed overall monetary losses and model estimates as well as the mean unitary monetary damage, i.e. the average ratio between loss (€) and building footprint area (m$^2$). The damage models developed for Italian contexts (INSYDE; Arrighi et al. 2018 and Secchia by Carisi et al., 2018) and CEPRI model are those providing the best estimation of the overall amount of monetary damage, although these models yield quite different results in terms of unitary damage except for INSYDE and Secchia MV which give both 85 €/m$^2$.

| Model | Total Monetary damage (M€) | Mean unitary monetary damage (€/m$^2$) |
|---|---|---|
| Observed | 6 | 60 |
| Arrighi et al. | 6 | 43 |
| Carisi_MV | 8 | 85 |
| Carisi_sqrtmono | 12 | 132 |
| CEPRI | 10 | 74 |
| Dutta et al. | 77 | 265 |
| FLEMO-ps | 16 | 176 |
| Fuchs et al. | 50 | 171 |
| INSYDE | 9 | 85 |
| Jonkman et al. | 14 | 49 |

**Table 2.** Observed losses versus monetary estimates with models.

The average of the 9 damage models is 22 M€ that is about four times the observed loss. The model by Dutta et al., (2003) provides the higher estimate, more than twelve times the observed 6 M€. These differences can be easily observed also in the maps of Fig. 1-2, where the model outcomes and observed losses are represented. Given the number of maps, the results have been separated into two figures to ensure readability.

Figures 1-2 show with the same colour scale the estimated unitary losses (Fig. 1-2, panels b to j) and the observed losses (Fig. 1, panel a).

Also in the case of the model by Arrighi et al. (2018), which provides the closest estimate of the overall losses, the maps (Fig. 1, panels a, b) show several differences. In fact, although the estimates are close to observations we may notice that the model behaves 'smoothly' where water depths are quite homogenous (see the right hand side of the map, panel b) while observed losses (panel a) appear more variable in space, with very high and very low damages close one to another. This smoothing effect, although with different absolute values can be observed in all models, highlighting that single-building scale flood damage estimation is very challenging for modellers given the intrinsic variability and uncertainty of exposure and vulnerability at such small scale.

## 5 Conclusions

The blind test suggests that model transferability depends on the similarity between the area of implementation and the calibration context. In fact, models developed for the Italian studies performed generally better than others. Nevertheless, the maps show that models provide a smoother estimation with respect to actual claims, which is affected by high spatial variability and uncertainty at single-building scale.
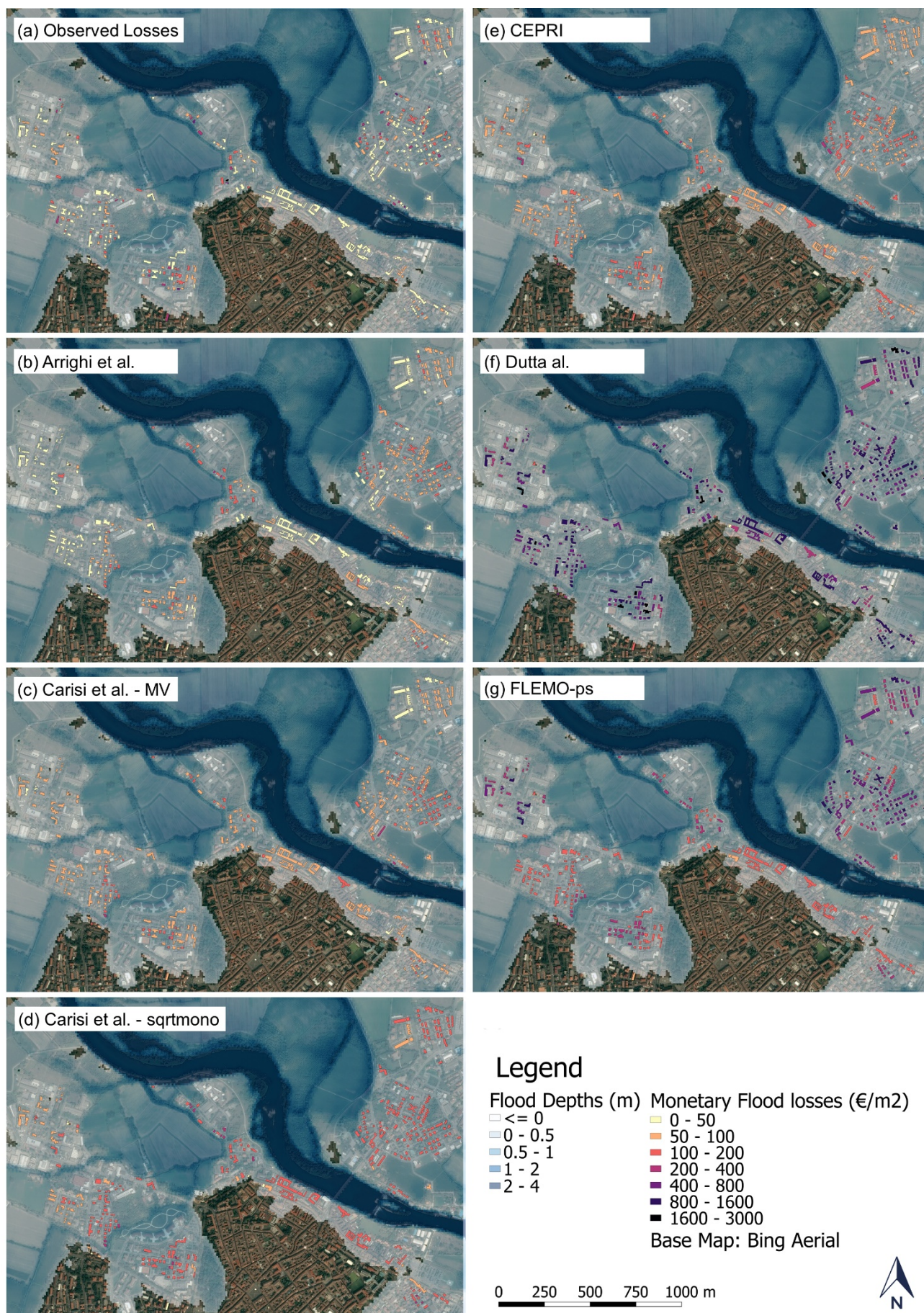
**Figure 1.** Comparative maps of unitary damage model estimates (b-g) and observed losses (a) (part 1)

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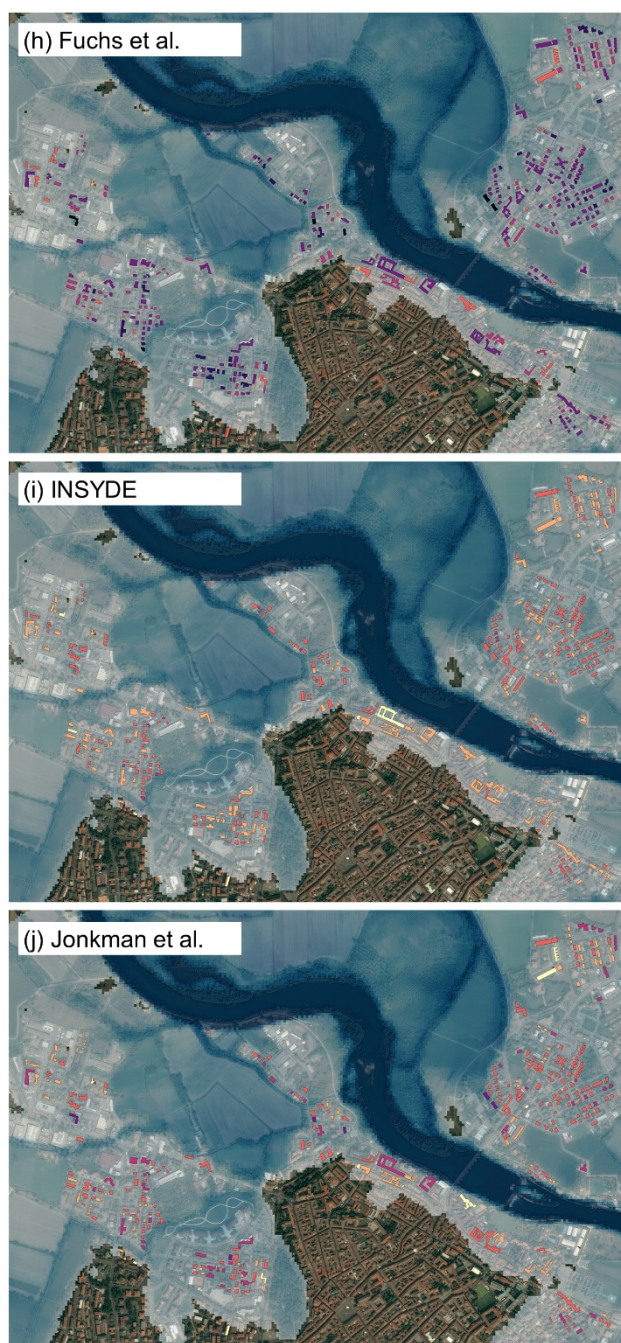
**Figure 2.** Comparative maps of unitary damage model estimates (h-j) (part 2)

This result suggests that a decrease in scale of application, e.g. census section (i.e. building block) or neighbourhood, could have positive effects in terms of capability of intercepting mean loss values.

Literature (e.g. Merz et al., 2013) generally suggests that including more variables in the models can improve accuracy, however in this blind test the simpler models (Carisi-sqrtmono or Jonkman et al., 2008) provide estimates comparable to multi-variable models (e.g. FLEMO-ps, CEPRI).

Further research could better investigate scale effects and observation uncertainties to improve the understanding of flood damage estimation.

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