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The effect of damage functions on urban flood damage appraisal

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Abstract

Flooding damage appraisal can been obtained by interpolating real damage data caused by historical flooding events or accounting the effects of a flood in terms of the depreciation of assets. Most often, the expected damage is evaluated by means of damage functions describing the relationship occurring between the damage and hydraulic characteristics of flood. The present paper aims to evaluate the uncertainty linked to the choice of the depth-damage function adopted in the flood damage analysis. Several possible depth-damage function formulations were selected in literature and applied to historical flooding events monitored in the "Centro Storico" catchment in Palermo (Italy).

Keywords: Flood damage; damage curve;uncertainty analysis; depth-damage function.

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1. Introduction

As result of the ongoing climate change and imperviousness of urban environment, frequency and impacts of urban flooding have increased in the last decades rising the interest of researchers and practitioners on this topic. A sustainable management of flooding in urban areas plays an important role in protecting people safety and their socio-economic activities.

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According to a proactive management of natural disasters, the European Directive 2007/60/EC (on the assessment and management of flood risks) invited Member States to identify the basins at risk of flooding and to draw up the related flood risk maps by 2013. In addition the EU legislation requires that flood risk management plans focused on both protection and prevention issues have to be developed and come into force by 2015. In such contest, the hydraulic analysis of urban flooding phenomena and the evaluation of the expected damages offer essential information both for stakeholders and for involved population. A quick estimation of flood damage may support the first ones in allocating resources for recovery and reconstruction after a flooding event or in planning adequate flood control measures in long term and in carrying out reliable cost-benefit analysis of these measures (Dutta et al., 2003; Buchele et al., 2006). At the same time the knowledge about the expected consequences of a flooding may facilitate the birth of a flood resilient society, that is the preparedness of involved people about flood risks and damages and how to act in the event of a flood (La Loggia et al, 2012).

Nowadays, the international literature includes several procedures for flood damage estimation in urban areas which often differ about methods adopted, aims pursued and availability of source data required. A rough classification can be done between ex-post or ex-ante analysis. In the first case, a damage appraisal at local scale is obtained by accounting in detail the object-specific damages after a flooding event. This kind of analysis is usually focused to allocate resources for recovery and reconstruction after the calamity event. Results are specific of the investigated area and usually affected by several errors due to a recurrent overestimation of immediately revealed damages (such as to household furnishing) and to an underestimation of the flood effects on buildings in long term (such as the depreciation of assets). In the latter case, ex-ante analysis provides the expected damage for a potential flooding event in the investigated area. The expected damage results from an a-priori appraisal obtained by interpolating real damage data related to historical flooding events (Meyer and Messner, 2006; Nascimento et al., 2006;) or accounting the effects of a flood in terms of the depreciation of assets (based on historical values or replacement values) or a percentage of the market value of the flooded properties etc. (Oliveri and Santoro, 2000).

In this kind of analysis, the expected flood damage is usually evaluated by means of damage functions (Apel et al., 2006, Dawson et al., 2008; de Moel and Aerts, 2011). Damage functions describe the relationship occurring between the level of damage and hydraulic characteristics of flood e.g. the flooding depth, or the combination of water depth and velocity, or the duration (Dutta et al., 2003), or the load of sediments etc. with respect to different land uses, characteristics and types of harmed goods (buildings, household furnishings, vehicles, etc.) and social and economic conditions of the affected area (Oliveri and Santoro, 2000). In practical application, analysis is usually focused only on direct tangible damages on public and private properties (e.g., buildings, cars, roads) as a function of inundation depth that is considered as determinant factor for the damage occurrence (Buchele et al 2006). Direct tangible damage are preferred because easily assessable in terms of monetary costs and linkable to flooding hydraulic features (Penning-Rowsell et al. 2003; Merz,et al., 2004; Meyer and Messner, 2006; Nascimento et al., 2006). Depth-damage functions are normally defined by interpolating flooding depth and damage data usually obtained by means of systematic survey procedures that analyze historical flood events or insurance claims data, or synthetic damage data (resulted by a-priori estimating the potential effects of a given flood depth in the investigated area). Several regression laws with different level of simplification can be used as depth-damage functions thus influencing the damage appraisal obtained. Moreover, flooding data are often piecemeal, affected by measurement errors and spatially aggregated because many parts of the system are not accessible during flooding (Freni et al., 2006). The lack of large databases in most cases is overcome by combining the output of urban drainage models and damage curves linking flooding to expected damage (Freni et al., 2010). In this way modeling uncertainty is merged to damage function uncertainty. As consequence, the obtained flood damage evaluations are usually affected by a degree of intrinsic uncertainty that cannot be realistically eliminated (Dotto et al, 2009).

In order to support decision makers in the planning of flooding mitigation measures and to increase the preparedness of involved people to flood consequence, a consistent analysis with regard to degree and causes of the uncertainty related to flood damage appraisal is necessary (Manson et al. 2002).

The present paper aims to evaluate the uncertainty linked to the choice of the depth-damage function adopted in the flood damage analysis. According to this aim the hydraulic analysis of several historical flooding event was carried out for a given case study. Thus, the related expected damage was evaluated by means of four different depth damage functions and the obtained results were compared.

2. The urban area investigated

The analysis proposed in the present study was applied to a case study an highly urbanized area of the city of Palermo (Italy). The “Centro Storico” of Palermo (Italy) is the oldest part of the city, strongly urbanised and with a very old drainage system, which receives both storm and waste water also from upstream less urbanized watersheds; local surface flooding due to the system insufficiency often occurs even for high-frequency rainfalls. Due to the system’s surcharge, during 1993-2008, several parts of the watershed were affected by about 30 flooding events for which by querying fire brigades and insurance companies an accurate database about flooded area, water depth and volume, duration and damaged properties have been collected (Freni et al., 2010). Inside the analysed area is located the Parco d’Orléans rain gauge, operational since 1993 with a temporal resolution of 1 minute. To simulate the urban drainage-system behavior, in the present study, a numerical model based on the SWMM software (Huber and Dickinson, 1988) and adopting a dual drainage approach (Djorgević et al., 1999; Leandro et al., 2009, Freni et al., 2010) was adopted. Calibration model was carried out on the flood levels and volumes measured by Municipal Fire Brigades during 28 small flood events in the studied area between 1993-2008 (Fontanazza et al., 2011). Fig. 1 shows the flooded areas, while Table 1 reports the mean water depths and flooding frequencies.

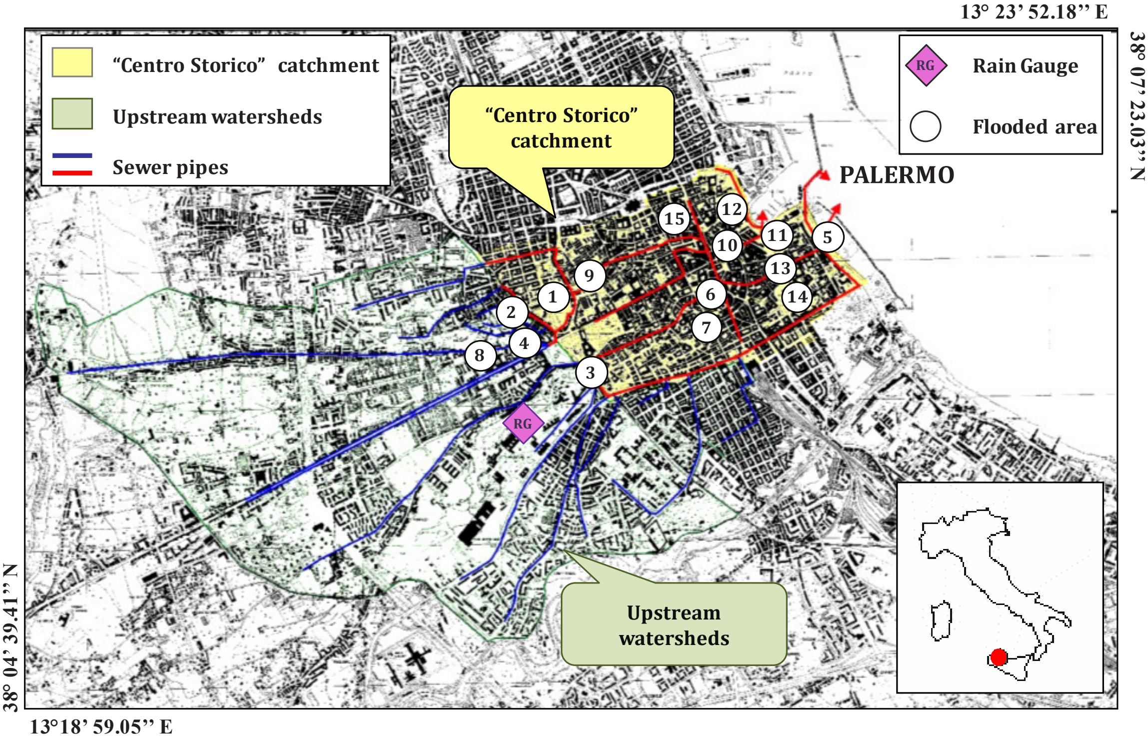

Fig. 1. The case study: the Centro Storico catchment, with flooded areas

Table 1. Frequency and mean flooding depth at different locations in the analysed catchment

Flooded area	Mean flooding depth [m]	Flooding frequency [n°flooding/yrs]	Flooded area	Mean flooding depth [m]	Flooding frequency [n°flooding/yrs]	Flooded area	Mean flooding depth [m]	Flooding frequency [n°flooding/yrs]
1	1,38	1,87	6	0,25	1,87	11	0,22	1,80
2	0,60	1,87	7	0,38	4,00	12	0,38	1,87
3	0,44	1,83	8	0,38	1,87	13	0,35	1,87
4	0,40	1,80	9	0,37	1,80	14	0,27	1,80
5	0,53	1,80	10	0,20	1,40	15	0,26	1,47

3. Depth-damage functions

Although depth-damage functions should be strictly applied for the analysis of the case study in which data were collected, the extrapolation to similar urban areas is a common practice in literature (Apel et al., 2006). Frequently, advanced hydraulic models, able to simulate flooding propagation in urbanized watersheds, are adopted to obtain simulated flooding data with regard to not recorded events or to ungauged urban areas. Several procedures propose to assess flood damages in urbanized watersheds by combining the flood depth-damage curves and the outputs of urban flood models (Jonkman et al., 2008; Prince and Vojinovic, 2008; Freni et al., 2010). The complexity of the flood propagation processes in urban watersheds and the limited amount of data available for model calibration may lead to high uncertainty in the model results (Lipime –Kouyi et al., 2009; Maksimović et al., 2009; Leandro et al., 2009, Freni et al, 2010). However, as stated by Freni et al.,2010 the use of detailed hydraulic models might not be justified because of the higher computational cost and the significant uncertainty in damage estimation curves. This uncertainty occurs mainly because a large part of the total uncertainty is dependent on depth-damage curves.

In order to investigate the uncertainty share linked to the damage curve shape adopted in the analysis, different function types such as linear, polynomial-2ord, exponential and power with upper limit functions were analyzed. Moreover, the main sources of uncertainty related to data availability were examined reducing the damage database by the “leave-one-out” approach: 464 families of curves were obtained by excluding information drawn from one flooding location or one flooding event. Then, depth-damage curves were obtained using the least squares minimisation approach to interpolate insurance claims data related to 28 historical flooding event affecting the investigated watershed. Data for vehicles and movable goods on properties were interpolated separately. For each adopted curve law (linear, polynomial–2ord, exponential and power) Fig. 2 and 3 show the resulting uncertainty bands (red lines) for the 5th and 95th percentiles together with the median curve (black line), and in Table 2 are summarized the corresponding average uncertainty band width referred to the median damage curve.

For vehicles, the uncertainty on the estimation of depth-damage curves was low and fell in the range of 4-8% of the average estimated damage value. Linear formulation provides the smaller width of the uncertainty band (on the average equal to 4%) while the exponential formulation provides the highest values (on the average equal to 8%). For goods inside buildings, the uncertainty on the estimation of depth-damage curves was relevant with values higher than 30% of the average estimated damage value. For high flood depth (h >1 m), all functions revealed a wide range of uncertainty with values around 30% for polynomial-2ord law and around 100% for exponential. This behavior is due to the few flooding data available thus increasing the uncertainty.

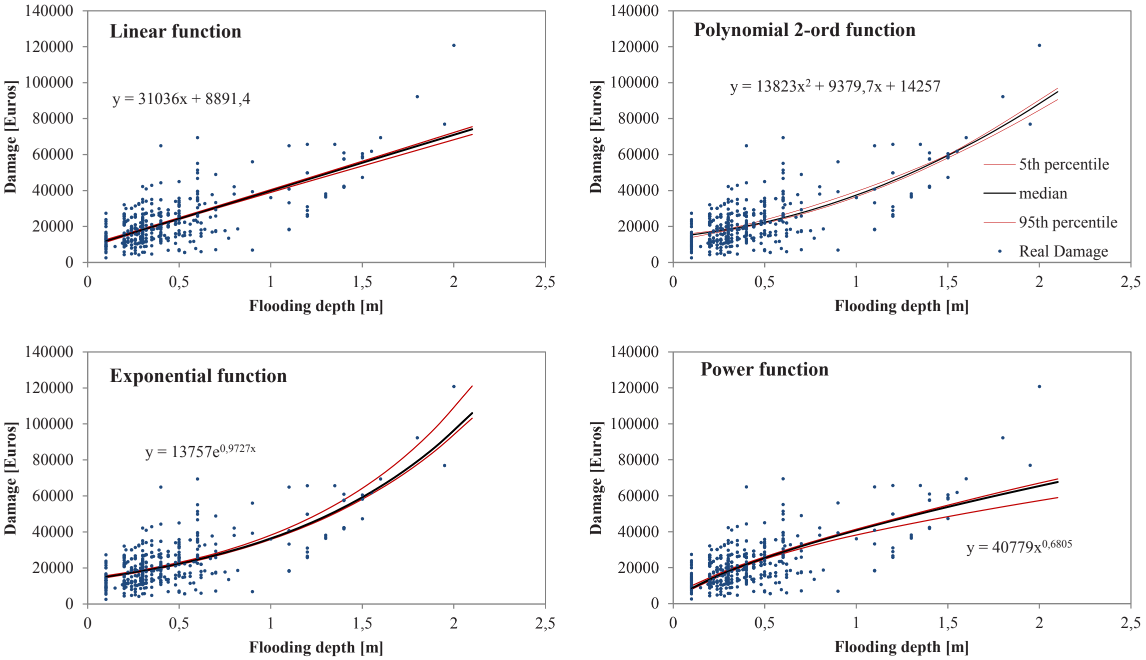

Fig. 2. Percentiles of Damage curves for vehicles

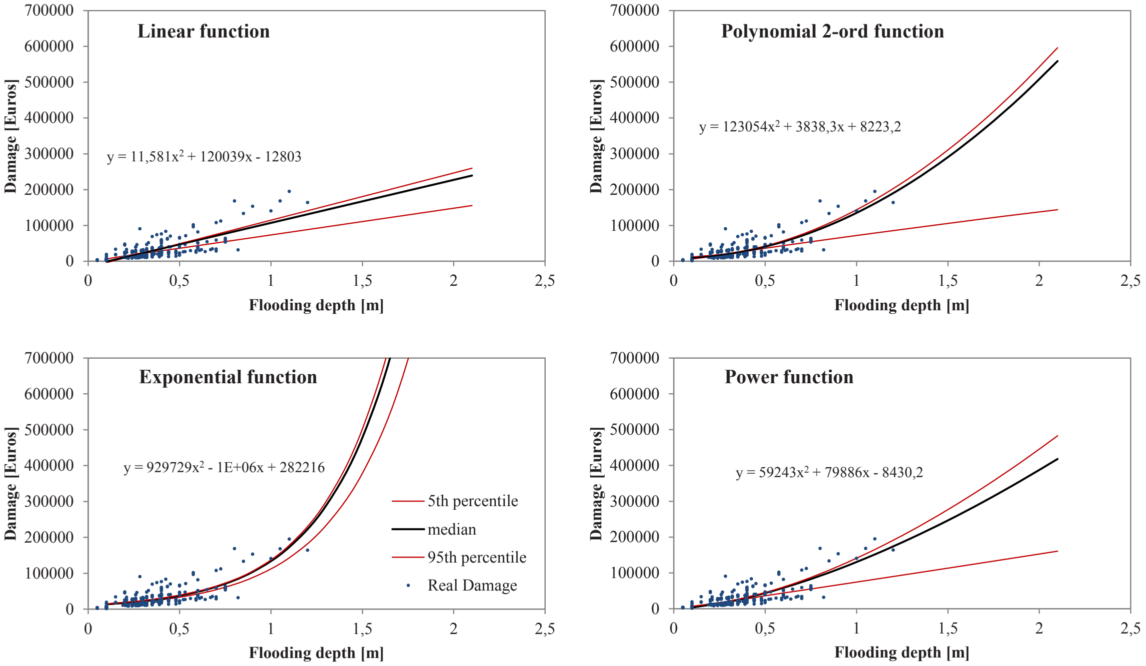

Fig. 3. Percentiles of Damage curves for goods inside buildings

Table 2 Average uncertainty band width referred to median damage curve for vehicles and goods inside buildings

Flood depth [m]	vehicles				goods inside buildings			
	average uncertainty band width referred to median damage curve				average uncertainty band width referred to median damage curve			
	linear	polynomial-2ord	exponential	power	linear	polynomial-2ord	exponential	power
0,3	5,7%	2,2%	2,1%	5,4%	12,6%	13,8%	19,1%	10,4%
0,5	4,0%	10,3%	11,4%	8,3%	26,9%	22,2%	22,1%	15,2%
0,7	3,5%	12,0%	13,1%	9,6%	33,7%	27,1%	7,8%	33,8%
0,9	3,8%	10,2%	10,5%	8,9%	37,2%	29,7%	15,0%	47,8%
1,1	4,0%	6,1%	5,9%	6,7%	39,4%	31,5%	42,4%	57,7%
1,3	4,4%	1,2%	0,3%	4,9%	40,7%	33,0%	72,4%	65,0%
1,5	4,8%	4,8%	5,5%	3,1%	41,7%	34,1%	104,2%	70,6%
1,7	5,1%	10,3%	10,9%	4,6%	42,5%	35,0%	137,4%	74,7%
1,9	5,5%	16,1%	16,3%	6,0%	43,0%	35,9%	171,9%	78,1%

4. Analysis of results

The analysis was carried out comparing the uncertainty provided by the formulation of uncertainty curves and by the model itself. In order to incorporate the modeling uncertainty, the classical GLUE approach (Beven and Binley, 1992; Freni and Mannina, 2010). 1000 Monte Carlo simulations were carried out using random parameter values picked from uniform distributions in the ranges provided in Table 3.

Table 3 Variation ranges and measuring units of the calibrated model parameters

Parameters	Unit.	Min	Max
Impervious area surface storage	mm	0.5	2.0
Pervious area surface storage	mm	3.5	8.5
Impervious area Manning's roughness	-	0.020	0.033
Pervious area Manning's roughness	-	0.025	0.050
Max infiltration rate (Horton)	mm/h	62.0	117.2
Saturated soil infiltration rate (Horton)	mm/h	12.2	22.7
Underground drainage system Manning's roughness	-	0.014	0.025
Surface channel Manning's roughness	-	0.021	0.034

Modeling efficiency for each model run was computed by means of Nash – Sutcliffe (NS) criterion (Nash and Sutcliffe, 1970). Once all the modeling runs were carried out, likelihood posterior distributions of modeling outputs (e.g. the total flooding damage) can be obtained filtering all non-behavioural simulations (being characterized by negative NS criterion), ordering the simulations against the modeling output value and cumulating the NS values to unity (refer to Beven and Binley, 1992, for details regarding the procedure for obtaining posterior likelihood distributions).

The uncertainty provided by the damage curves commented in the previous paragraph and the modeling uncertainty was compared in tables 4 – 7. For one of the monitored flooding events, table 4 and 5 reports the relative error between the modeled and the measured damage considering different percentiles of model parameter posterior likelihoods and different depth damage curves. Data were divided for vehicles and buildings because uncertainty levels are different and the definition of depth damage curves variability is higher for this second class of exposed elements.

Table 4. Flooding event 12 August 1997: error in flood damage for vehicles obtained by different function types of damage curve applied to measured and simulated flooding depths (percentiles of Monte Carlo simulations and max efficiency model).

Flooding event 12 August 1997

Functiontype	Damage curve percentile	Error in flood damage related to simulated flooding depths (percentiles of Monte Carlo simulations and max efficiency model)						Error in flood damage related to measured flooding depths
		5th percentile	25th percentile	50th percentile	75th percentile	95th percentile	H max model efficiency	H mis
linear	5th percentile	-27,3%	-20,0%	-14,4%	-7,5%	2,9%	**-14,1%**	**-14,0%**
	median	-25,7%	-18,2%	-12,4%	-5,2%	5,6%	**-12,1%**	**-11,9%**
	95th percentile	-23,9%	-16,2%	-10,3%	-3,1%	7,9%	**-10,0%**	**-9,9%**
polynomial-2ord	5th percentile	-22,9%	-16,8%	-12,3%	-6,2%	3,5%	**-12,1%**	**-12,0%**
	median	-18,2%	-12,4%	-7,9%	-1,9%	7,7%	**-7,7%**	**-7,6%**
	95th percentile	-14,0%	-8,0%	-3,4%	2,7%	12,5%	**-3,3%**	**-3,2%**
exponential	5th percentile	-20,1%	-14,3%	-9,8%	-3,7%	6,1%	**-9,6%**	**-9,6%**
	median	-18,9%	-12,9%	-8,3%	-2,1%	7,9%	**-8,1%**	**-8,2%**
	95th percentile	-18,0%	-11,4%	-6,2%	0,6%	12,0%	**-6,0%**	**-6,1%**
power	5th percentile	-34,8%	-25,8%	-19,5%	-12,0%	-0,9%	**-19,2%**	**-19,2%**
	median	-34,4%	-24,7%	-17,6%	-9,2%	3,3%	**-17,3%**	**-17,4%**
	95th percentile	-32,5%	-22,6%	-15,4%	-6,7%	6,0%	**-15,0%**	**-15,1%**

Table 5. Flooding event 22 August 1997: error in flood damage for vehicles obtained by different function types of damage curve applied to measured and simulated flooding depths (percentiles of Monte Carlo simulations and max efficiency model).

Flooding event 22 August 1997

Function type	Damage curve percentile	Error in flood damage related to simulated flooding depths (percentiles of Monte Carlo simulations and max efficiency model)						Error in flood damage related to measured flooding depths
		5th percentile	25th percentile	50th percentile	75th percentile	95th percentile	H max model efficiency	H mis
linear	5th percentile	-27,8%	-18,8%	-11,0%	-2,4%	16,3%	**-11,3%**	**-13,7%**
	median	-26,3%	-16,8%	-8,7%	0,2%	19,6%	**-9,0%**	**-11,6%**
	95th percentile	-24,4%	-14,9%	-6,7%	2,4%	22,1%	**-7,0%**	**-9,5%**
polynomial-2ord	5th percentile	-25,5%	-17,5%	-9,4%	0,6%	26,8%	**-9,8%**	**-11,8%**
	median	-21,2%	-13,4%	-5,2%	5,1%	32,5%	**-5,6%**	**-7,5%**
	95th percentile	-17,0%	-9,0%	-0,6%	9,7%	37,3%	**-1,1%**	**-3,1%**
exponential	5th percentile	-22,6%	-14,6%	-5,3%	8,2%	57,6%	**-5,8%**	**-8,5%**
	median	-21,5%	-13,2%	-3,6%	10,2%	61,2%	**-4,2%**	**-7,0%**
	95th percentile	-20,8%	-11,6%	-0,5%	15,9%	79,7%	**-1,1%**	**-4,4%**
power	5th percentile	-32,2%	-22,2%	-14,0%	-5,7%	10,6%	**-14,2%**	**-17,7%**
	median	-32,2%	-20,9%	-11,7%	-2,1%	16,9%	**-12,0%**	**-15,7%**
	95th percentile	-30,2%	-18,7%	-9,2%	0,5%	19,8%	**-9,5%**	**-13,3%**

By looking at Table 4, the following considerations can be carried out :

- Flooding damage is generally underestimated by the model considering that, using the median of depth- damage curves and of model simulations, the computed damage is between 17% and 8% lower than the measured one.

- This underestimation is mainly due to the interpolation of depth damage curves considering that, even using measured flooding depths, the total damage is underestimated.
- The agreement between the numerical flooding model and the measured flooding depths is good considering that the total damage estimated by the model and using the measured flooding depths is equivalent;
- The uncertainty range between 5th and 95th percentiles of modeling uncertainty is 10 times higher than the equivalent range due to depth – damage curves thus demonstrating that the great part of uncertainty still relies in the numerical model of the physical processes.
- The uncertainty provided by the selection of the damage curve formulation impacts on damage estimation in the range of 7-8% that is comparable with the uncertainty in the estimation of damage curve parameters after the formulation has been selected.

Similar considerations can be extrapolated looking at the other analysed events. Table 5 shows the results obtained for the event of 22nd August 1997. The selection of a specific formulation of depth – damage curves does not provide a relevant impact on the estimation of total damage and on uncertainty in such estimation.

Different comments should be given looking at damage on movable goods on properties (Table 6 and 7):

- The damage estimation is highly underestimated (averagely 30%) and a large difference can be seen between different formulations; the exponential formulation provides the smaller underestimation in the range of 5% in the median, while the linear formulation provides the highest underestimation of about 30%.
- Also uncertainty is dependent on the selected formulation ranging between 10% and 20% in the median and the mixture between the modeling uncertainty and the damage curve uncertainty provides larger uncertainty bands in this case if compared to the vehicle damage
- The exponential law seems to be the best choice also for the second analysed event even if the estimation of depth – damage curve parameters seems to be a source of uncertainty more significant in this case than in the analysis of vehicle damage.

Table 6. Flooding event 12 August 1997: error in flood damage for goods inside buildings obtained by different function types of damage curve applied to measured and simulated flooding depths (percentiles of Monte Carlo simulations and max efficiency model).

Flooding event 12 August 1997								
Function type	Damage curve percentile	Error in flood damage related to simulated flooding depths (percentiles of Monte Carlo simulations and max efficiency model)						Error in flood damage related to measured flooding depths
		5th percentile	25th percentile	50th percentile	75th percentile	95th percentile	H max model efficiency	H mis
linear	5th percentile	-67,3%	-56,5%	-48,1%	-37,7%	-21,5%	**-47,8%**	**-46,4%**
	median	-66,0%	-49,1%	-35,8%	-19,7%	5,7%	**-35,4%**	**-33,3%**
	95th percentile	-61,0%	-42,8%	-28,6%	-11,2%	16,0%	**-28,1%**	**-25,8%**
polynomial-2ord	5th percentile	-60,7%	-50,1%	-41,9%	-31,9%	-16,3%	**-41,6%**	**-40,3%**
	median	-43,0%	-30,0%	-19,4%	-4,6%	22,5%	**-19,1%**	**-15,2%**
	95th percentile	-38,0%	-24,4%	-13,2%	2,4%	31,1%	**-12,9%**	**-8,8%**
exponential	5th percentile	-42,9%	-31,8%	-22,2%	-8,7%	17,8%	**-21,9%**	**-18,1%**
	median	-36,3%	-22,9%	-11,3%	5,2%	37,6%	**-11,0%**	**-6,3%**
	95th percentile	-36,4%	-22,8%	-10,7%	6,4%	40,0%	**-10,4%**	**-5,4%**
power	5th percentile	-58,6%	-48,4%	-40,5%	-30,8%	-15,1%	**-40,5%**	**-39,1%**
	median	-55,5%	-40,6%	-28,7%	-13,0%	15,1%	**-28,9%**	**-25,4%**
	95th percentile	-54,7%	-39,0%	-26,3%	-9,5%	21,0%	**-26,6%**	**-22,7%**

Table 7. Flooding event 22 August 1997: error in flood damage for goods inside buildings obtained by different function types of damage curve applied to measured and simulated flooding depths (percentiles of Monte Carlo simulations and max efficiency model).

Flooding event 22 August 1997								
Function type	Damage curve percentile	Error in flood damage related to simulated flooding depths (percentiles of Monte Carlo simulations and max efficiency model)						Error in flood damage related to measured flooding depths
		5th percentile	25th percentile	50th percentile	75th percentile	95th percentile	H max model efficiency	H mis
linear	5th percentile	-52,5%	-36,9%	-23,5%	-8,1%	23,2%	**-23,9%**	**-30,5%**
	median	-47,9%	-23,5%	-2,5%	21,5%	70,4%	**-3,2%**	**-13,5%**
	95th percentile	-40,8%	-14,6%	7,9%	33,7%	86,4%	**+7,2%**	**-3,8%**
polynomial-2ord	5th percentile	-43,4%	-28,1%	-14,9%	0,0%	30,1%	**-15,4%**	**-21,9%**
	median	-38,7%	-24,1%	-8,8%	12,0%	63,7%	**-9,5%**	**-13,8%**
	95th percentile	-33,3%	-18,1%	-2,0%	19,9%	74,7%	**-2,7%**	**-7,2%**
exponential	5th percentile	-34,8%	-25,0%	-15,2%	-1,7%	33,6%	**-15,6%**	**-18,5%**
	median	-28,4%	-17,2%	-5,7%	10,1%	52,0%	**-6,2%**	**-9,4%**
	95th percentile	-29,2%	-17,8%	-6,2%	9,9%	52,9%	**-6,6%**	**-9,9%**
power	5th percentile	-42,8%	-28,1%	-15,3%	-0,5%	29,9%	**-15,7%**	**-21,9%**
	median	-49,5%	-30,0%	-10,9%	13,3%	68,8%	**-11,7%**	**-18,7%**
	95th percentile	-51,1%	-30,8%	-10,8%	14,8%	74,7%	**-11,7%**	**-18,7%**

5. Conclusions

The present paper analysed the uncertainty related to the definition and estimation of the depth – damage curves in urban flooding analysis. The analysis was applied to a real case study where damage and flooding data were collected. The cases of vehicle and building damage were split because a larger variability of measured damage data was verified in this second case. Four formulations were compared and their uncertainty was analysed against the common modeling uncertainty in the estimation of flooding depths.

Generally, modeling uncertainty is still larger than the uncertainty related to depth – damage curves. In the case of building damage, such difference is smaller because a larger variability of damage data can be found related to similar flooding depths. This is due to the fact that the street flooding depth is correlated to the internal building damage neglecting all the processes (obstructions or privileged flooding paths) that can increase or reduce the impact of flooding inside the building. Moreover a larger variability of damaged values may be experienced on buildings with respect to vehicles. In this last case, the selection of a specific formulation does not provide any relevant advantage both in the estimation of damage and in its related uncertainty. Differently the exponential formulation seems to be best for the evaluation of building damage. On a theoretical basis, this formulation is not physically robust because it states the progressive increase of marginal damage with the increase of flooding depth. This is probably due to the fact that the available data mainly refers to small flooding events that may be characterized by irrelevant damage due to very small flooding depths (less than 20 cm) and much large damage when flooding depths increases and the electric system is compromised..

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