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Flood damage curves: new insights from the 2010 flood in Veneto, Italy

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Abstract

Flood damage modelling is becoming an essential component in flood risk management. However damage assessments are affected by large uncertainty, mainly related to the use of depth–damage functions. In some countries, where no site-specific curves are available, a transfer of damage models developed from other areas is required, adding extra uncertainty in the modelling process. This paper discusses the transferability in space of damage curves from literature, with a focus on 'function uncertainty', pointing out, especially for mesoscale ones, the lack of detailed information in terms of flood and/or building characteristics that can allow to identify the conditions of applicability of the models. New site-specific depth–damage functions are then developed for the residential sector, at meso- and microscale, based on damage data from the 2010 flood in Veneto, Italy. The application of the new curves reveals a better performance of the mesoscale model compared with the more detailed microscale one, probably due to the small extent of the inundated area.

Introduction

Floods are recognised as one of the most damaging natural hazards, responsible in the decade 1998–2009 for an economic damage exceeding 50 billion Euro and 1000 fatalities in Europe (EEA, 2010), and they are expected to become more frequent and severe in the future due to climate change and growing urbanisation.

In recent years, the contribution of damage modelling is thus becoming of essential importance in the field of flood risk management, for decision-making processes and for developing flood control policies and strategies. This role has been emphasised by the European Floods Directive (European Commission, 2007), which requires member states to prepare floods risk maps by 2013 and to establish flood risk management plans focused on prevention, protection and preparedness by 2015, taking also into account environmental, social and cost-effectiveness aspects (e.g. related to the implementation of flood mitigation measures). This means that the 'classical' concept of flood protection, based on design standards related to predefined return periods, is increasingly being replaced by more comprehensive understanding of the risk over a certain period (Plate, 2002; Sayers *et al.*, 2002).

According to the directive, flood risk is defined as 'the combination of the probability of a flood event and of the potential adverse consequences for human health, the environment, cultural heritage and economic activity associated with a flood event'.

These consequences, or damages, are usually divided in two classes, tangible and intangible damages, depending on the possibility of assessing them in monetary terms. A further classification distinguishes losses in direct and indirect damages, with the first resulting from the physical contact of water with exposed elements and the second induced by the flood, but occurring, in space and time, outside the event (Smith and Ward, 1998; Jonkman *et al.*, 2008; Meyer *et al.*, 2013). Even though it is acknowledged that intangible and indirect damages can have an important contribution in total flood damage (DEFRA, 2005; Penning-Rowsell *et al.*, 2010), large part of the literature is focused only on direct tangible damages.

Three steps are required for economic analyses in flood risk assessments:

1. Accurate prediction of flood inundation, i.e. hazard definition, performed by hydrologic and hydraulic modelling;
2. Exposure analysis, which consists in the recognition of potentially damaged assets (information on the location, number and type of elements at risk) and attribution of economic values based on land use or individual objects;

3. Information on the susceptibility of the elements at risk against inundation characteristics, provided by the so-called damage curves (or vulnerability curves, depth–damage curves, loss functions), which define expected damage as a percentage of the maximum asset value (relative damage curves) or directly in monetary terms as absolute unit value of damages (absolute damage curves), as a function of water depth (other factors like flow velocity, inundation duration, presence of debris, contamination, implementation of precaution measures are rarely taken into account; Thieken *et al.*, 2005; Kreibich *et al.*, 2009).

These curves are nowadays considered as a standard approach for performing flood damage assessments (Smith, 1994). Messner *et al.* (2007) and Merz *et al.* (2010) showed that there is a wide range of damage models available in the literature for different sectors (e.g. agriculture, industry, residential, etc.) and levels (micro-, meso- and macroscale). Examples of relative damage curves, both empirically based on flood damage databases and/or on expert judgment, can be found in Germany with Rhine Atlas, Hydrotec and Flood Loss Estimation MOdel (FLEMO) models (ICPR, 2001; Hydrotec, 2001; Thieken *et al.*, 2008; Kreibich *et al.*, 2010), in the Netherlands with the Standard Method (Kok *et al.*, 2005) and the Damage Scanner (Klijn *et al.*, 2007) or in the USA with HAZUS-MH (Scawthorn *et al.*, 2006). Other curves have been developed by the JRC (HKV Consultants, 2007) for different European countries, based on historical data and literature review of existing studies. Absolute damage functions are used instead, e.g. in Australia (NR&M (Department of Natural Resources and Mines, Queensland Government, 2002) or in the UK (Penning-Rowsell *et al.*, 2010).

Nevertheless, as pointed out in several studies, large uncertainties affect damage modelling, due to the lack of consistent object-based damage data for the development of reliable damage models (Apel *et al.*, 2004, 2009; Merz *et al.*, 2004; Freni *et al.*, 2010; Bubeck *et al.*, 2011; de Moel and Aerts, 2011; Jongman *et al.*, 2012; Vorogushyn *et al.*, 2012; Cammerer *et al.*, 2013). In addition, it is worth noting that damage curves are site specific, which means that they are strictly valid for the context for which they have been developed. However, a transfer operation of damage models is usually required for performing economic analyses in countries where no local curves are available. In fact, it is not unusual to find flood damage assessment studies based on functions derived from other contexts: for example, in Giang *et al.* (2009) and Genovese (2006), Dutch curves were used for calculations in Vietnam and Czech Republic, respectively, or Japanese curves from Dutta *et al.* (2003) in a case study in Greece (Kourgialas and Karatzas, 2013).

Even though relative damage functions are preferred because they are easier to transfer from one country to another, provided that local values of exposed assets are given (Merz *et al.*, 2010), when applying them, attention should always be paid on the reliability of the results because of the large differences existing between the models.

Italy is an example of a country where no comprehensive study for the development of specific damage curves has been accomplished on the basis of extensive information on damage data (Molinari *et al.*, 2014), if excluding local studies limited to single events, as in Luino *et al.* (2009).

In this perspective, the present paper analyses the transferability to the Italian context of existing damage models in the literature, based on damage data from the 2010 Bacchiglione River flood in the Veneto Region (north-east of Italy) and gives new information for the development of site-specific curves for the residential sector, both at meso- and microscales.

2010 Bacchiglione flood event

From 31 October to 2 November 2010, the Veneto Region, in particular areas on the foothills and piedmont, were affected by persistent rain, producing a total rainfall accumulation that locally exceeded 500 mm, which resulted in the emergence of a high hydraulic stress in the region. This flood has been recognised as one of the largest and most serious events that have struck the pre-Alpine and foothill areas of Veneto in the last 50 years (ARPAV, 2010).

The impact on the population in lowland areas was very severe: three fatalities, many injuries and thousands people evacuated. Shortly after the event, the total flood damage in the region to private properties, economic activities and public infrastructures was estimated to be around 666 million Euro; this amount was then corrected to about 426 million Euro in July 2011 (Regione del Veneto, 2011), confirming the usual difference between initial damage estimates and final repair costs in postevent damage surveys (Downton and Pielke, 2005).

Case study area and damage data

The municipality of Caldogno, a town of about 11 000 inhabitants in the province of Vicenza (Figure 1), was selected for this study. In the 2010 flood, an estimated area of 3.3 km^2 was inundated, consisting of approximately 0.7 km^2 of urban area and 2.6 km^2 of agriculture and natural land cover. This resulted in a total damage to residential properties, economic activities, agriculture and public infrastructures equal to 25.7 million Euro (initial estimate was around 80.5 million Euro).

Official loss data, provided by the municipality of Caldogno, were based on the 'Quantification of damage' forms sent out by the authorities, in the frame of the loss compensation by the State. Damaged people were asked to report in these forms actual restoration costs, certified by

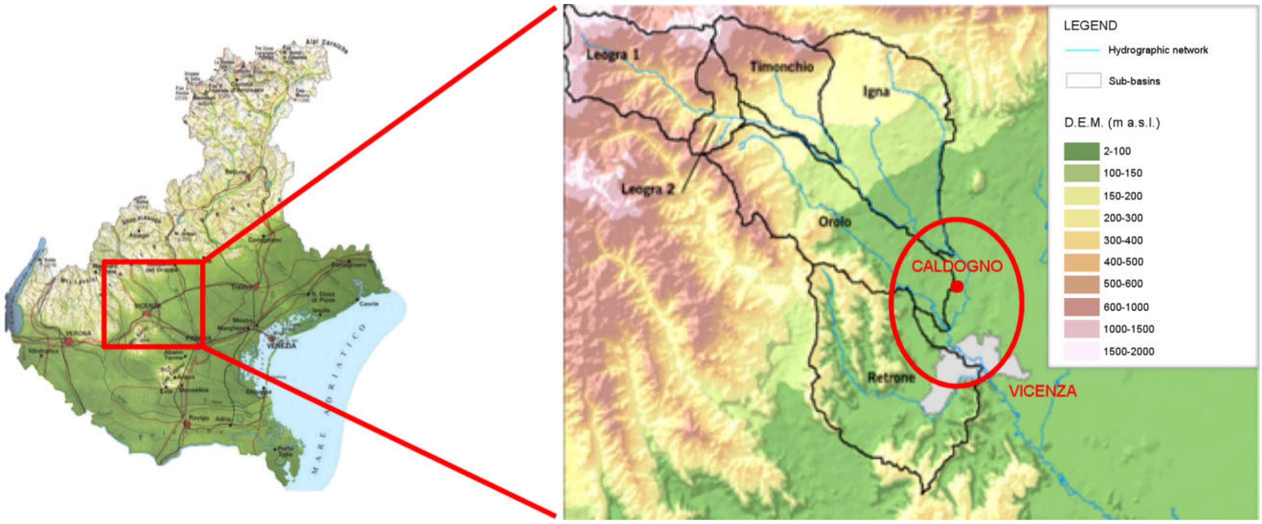

Figure 1 Investigation area overview.

original receipts and invoices of the expenses, which were then verified by municipal technicians on the basis of site inspections. In these forms, for each property, total damage was distinguished in building damage, damage to registered mobile goods (e.g. cars, etc.) and damage to building inventories.

In this study, attention was focused on residential damage, which constituted the bulk of total damage with 14.8 million Euro (not inclusive of registered mobile goods), for 319 damaged buildings distributed as follows:

- Multifamily, multistorey buildings, with and without basement (79 affected objects);
- Single-family detached houses ('villas'), with and without basement (91 affected objects);
- Single-family detached houses (lower quality buildings), with and without basement (61 affected objects);
- Semi-detached houses, with and without basement (70 affected objects);
- Continuous buildings, with and without basement (18 affected objects).

The characteristic structural types in the area were constituted by reinforced concrete and masonry buildings.

Inundation scenario

Using Infoworks RS (Innovyze, Broomfield, Colorado, USA), a coupled 1D/2D model of the study area was implemented in order to account for inundation characteristics between the municipalities of Caldogno and Vicenza, as no direct information on local flood depths was available.

In addition to the information from the Regional Technical Map (at 1:5000 scale), lidar data from the Italian Ministry of the Environment and from the competent Basin Authority were used for the description of the floodplain inundation part of the 1D/2D model. The geometry of the 1D river network domain was obtained from topographic surveys of 72 cross-sections of Timonchio, Orolo and Bacchiglione Rivers, including 20 bridges and 3 weirs.

Detailed information on the calibration of the hydrological and hydraulic model is reported in the study of Beta Studio (2012).

The reliability of the results was verified by means of additional information on the event, as follows:

- Hydrometric data registered at Ponte Angeli in Vicenza were used to evaluate the goodness of flow estimation;
- Aerial surveys of inundated areas in the municipalities of Caldogno and Vicenza and information from local authorities about flood dynamics were used for comparing modelled and observed inundation extents (Figure 2), revealing model ability in capturing the characteristics of the flood event, especially in built-up areas, with a flood area index (Dung *et al.*, 2011) of about 94%;
- Photos and videos of the event and interviews with affected population were used for the validation of the hydraulic model and for the comparison of local observed inundation depths with the output of the simulation run [as in Figure 2(b)].

The graph in Figure 3 provides the percentage of grid cells inundated with a water level within a specific 0.5 m interval, showing a large share of low water depths, with an average value of about 0.8 m.

Methodology

Damage modelling: mesoscale analysis

Because damage model validations are rarely performed and validation tests are often called for (Merz *et al.*, 2010;

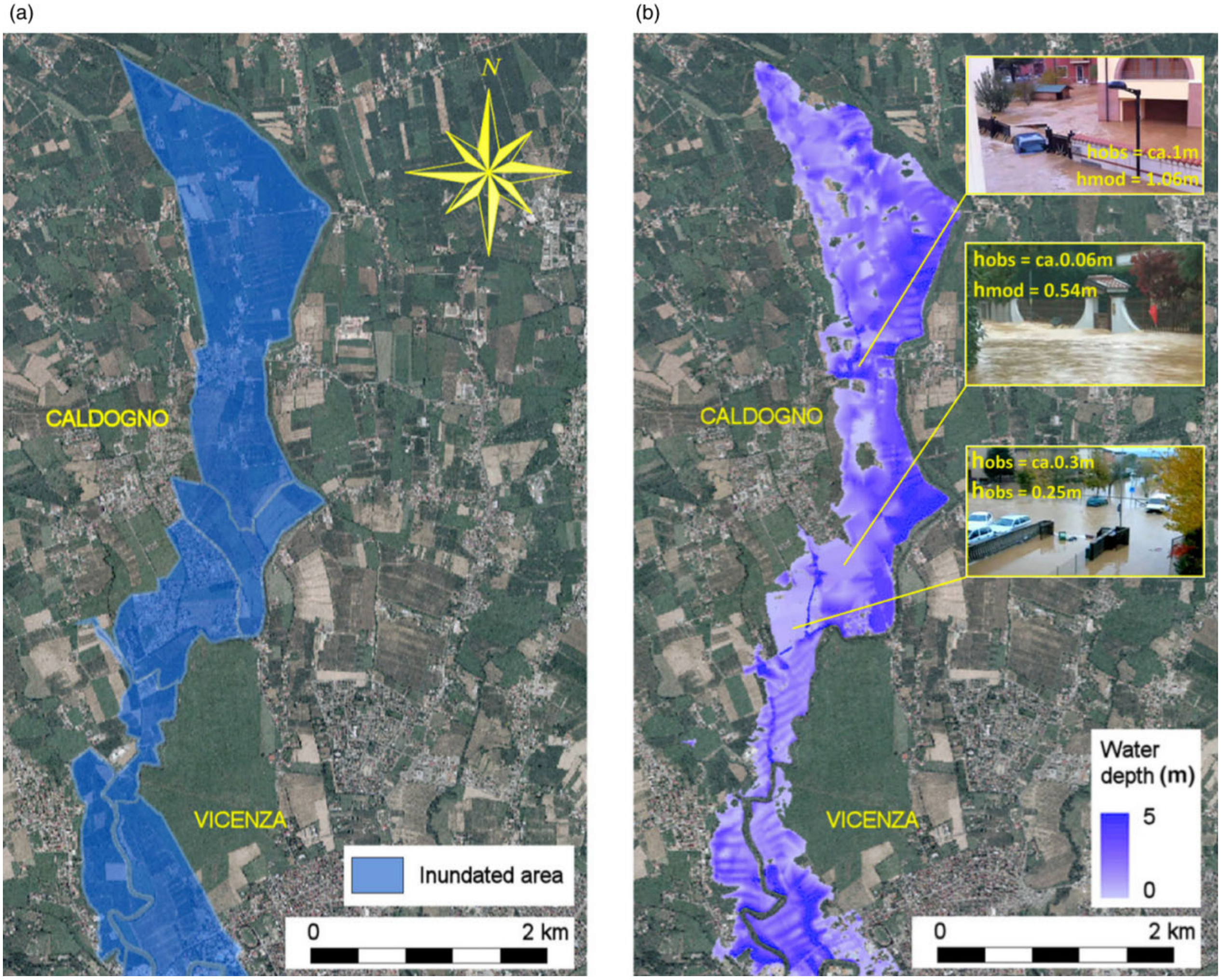

Figure 2 2010 Bacchiglione flood in Caldogno. (a) Survey of inundated area. (b) Modelled inundated area, with examples of a comparison between observed and calculated water levels.

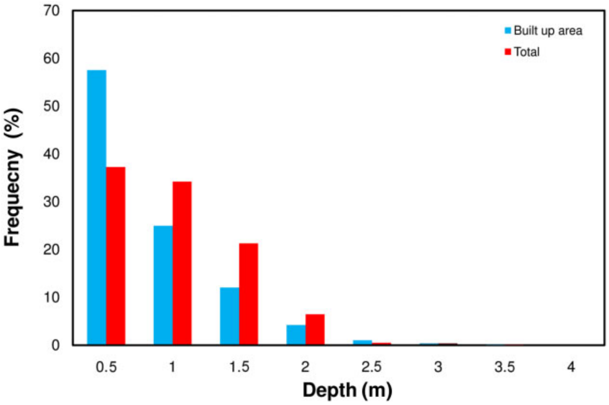

Figure 3 Histograms of simulated inundation depths in Caldogno, for built-up area only and for the total inundated area.

Jongman *et al.*, 2012; Cammerer *et al.*, 2013; Meyer *et al.*, 2013), the first issue that was addressed regarded the transferability in space of existing damage models in the literature. Reported losses to the residential sector were then compared with direct economic damages estimated by applying the following models: JRC model for different countries (HKV Consultants, 2007), Damage scanner model (Klijn *et al.*, 2007), Flemish model (Vanneuville *et al.*, 2006), FLEMOps model (Thieken *et al.*, 2008), Hydrotec model (2001), Rhine Atlas model (ICPR, 2001) and Standard Method (Kok *et al.*, 2005). A detailed description of the differences between these models can be found in the previous studies of Merz *et al.* (2010) and Jongman *et al.* (2012).

The aim of this analysis was to evaluate whether these damage models, developed for other countries, perform reasonably in the observed situation. In fact, even though empirical models could be more accurate when applied to a case study similar to their context of origin, in terms of building and flood event characteristics (Cammerer *et al.*, 2013), the topic of the transferability of damage models from one region or country to another remains an open question (Jongman *et al.*, 2012).

As the analysis was focused on residential damage, exposure information related only to built-up areas was extracted from the regional land-cover map (Regione del Veneto, 2009). The 51% of the inundated built-up area was comprised of residential discontinuous dense urban fabric, the 25% of discontinuous medium density urban fabric and the 24% of discontinuous sparse urban fabric.

Site-specific asset values were used for all the different damage functions, as the application of the original values of the models to an economically distinct region could lead to unreliable results, with significant over- or underestimation of the expected losses (Merz *et al.*, 2010; Jongman *et al.*, 2012; Cammerer *et al.*, 2013).

These economic values were assigned based on the identified land-use classes, adjusted for considering the actual building density in each unit (Jongman *et al.*, 2012), and

Table 1 Mesoscale analysis: residential asset values (€/m^2; building and inventory) for the different urban fabric areas

	Discontinuous dense urban fabric	Discontinuous medium density urban fabric	Discontinuous sparse urban fabric
Mean	281	237	146
Minimum	94	77	44
Maximum	578	352	303
80th percentile	341	305	210
20th percentile	211	186	77

local mean rebuilding/replacement values. Due to the lack of specific information, residential inventory values were estimated to be equal to 50% of the building value, according to other existing studies (USACE, 1992; Vanneuville *et al.*, 2006). Resulting asset values for the different urban fabric areas are reported in Table 1. For example, for discontinuous dense urban fabric land-use units, these values ranged from about 94 (minimum density) to 578 €/m^2 (maximum density), and a mean of 281 €/m^2.

Damage calculations were performed on a mesoscale raster-based approach. Damage curves from the selected models were used for relating flood water depth and the economic value of land-use units using the following procedure: first, the damage ratio of the exposed elements per grid cell was evaluated as a function of the magnitude of the event, as identified with the hydraulic model (5 × 5 m); then, economic losses were quantified by multiplying this ratio by the specific asset value assigned to the corresponding grid cell.

As second step, collected data for each inundated building in Caldogno were used for developing a site-specific mesoscale depth–damage curve for the residential sector (building and inventory), which was determined by following the procedure exposed below and illustrated in Figure 4:

- Potential maximum damage values were attributed to each of the land-use units, as identified in the previous section (i.e. residential discontinuous dense/discontinuous medium density/discontinuous sparse urban fabric areas), considering local mean rebuilding/replacement values, adjusted for considering local heterogeneity in building density in each unit. This implies that each residential land-use polygon was characterised by its own maximum damage potential: e.g. for the area indicated by an arrow in Figure 4 this value was equal to 339 €/m^2.

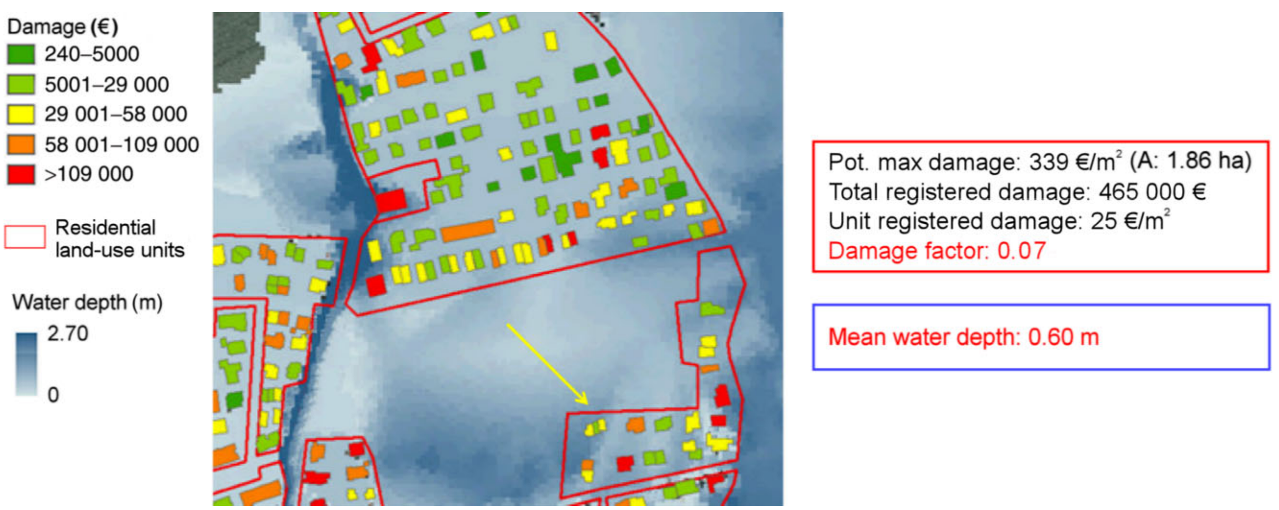

Figure 4 Example describing the procedure for the determination of the mesoscale damage curve.

- Once georeferenced, registered damages for each building were considered for determining the total damage in each land-use unit: e.g. in the polygon in Figure 4, equal to 465.000 €.
- Unit damage in each land-use unit was calculated by dividing total damage by polygon area: in the example, (465.000 €) / (18.600 m^2) = 25 €/m^2.
- The damage factor (i.e. the loss of value, expressed as a proportion of the maximum damage potential) in each land-use unit was obtained by dividing the unit damage by the potential maximum damage of the land-use unit: in the example, (25 €/m^2) / (339 €/m^2) = 0.07.
- At the same time, mean water levels in each area were calculated based on the results of the hydraulic model: in the example, 0.60 m.

Data points shown in Figure 5 are the result of the exposed procedure applied to all the 34 residential land-use units affected by the flood.

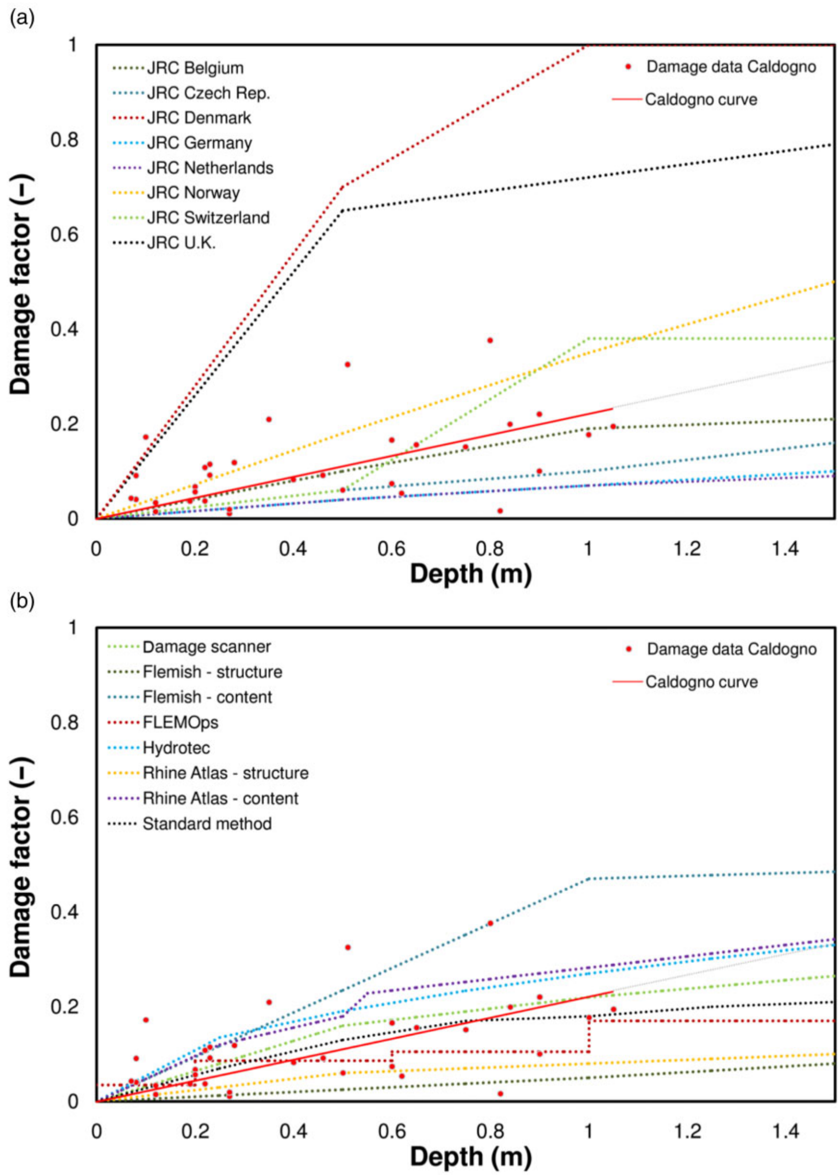

Figure 5 Mesoscale damage curve for the residential sector (building and inventory) from the 2010 Bacchiglione flood and comparison with other curves in the literature: (a) JRC curves (HKV Consultants, 2007); (b) Damage scanner model (Klijn *et al*., 2007), Flemish model (Vanneuville *et al*., 2006), FLEMOps (Thieken *et al*., 2008), Hydrotec (2001), Rhine Atlas model (ICPR, 2001) and Standard Method (Kok *et al*., 2005).

Damage modelling: microscale analysis

A more detailed, microscale analysis was then performed by integrating object-based water levels and damage data with information on building vulnerability.

Similar to what was shown at the mesoscale level, the topic of the transferability in space of damage models was investigated. Some damage functions, working at the building level and derived for different countries, were considered for the analysis, including the following: the US model of Debo (1982), the Japanese one of Dutta *et al.* (2003), the German FLEMOps (Thieken *et al.*, 2008) and other three specifically applied in damage assessment studies in Italy, i.e. the synthetic curves of Oliveri and Santoro (2000) and Arrighi *et al.* (2013) and the empirical one of Luino *et al.* (2009). These curves were then applied, at the microscale for each building, to the inundation scenario under consideration and combined with information on local rebuilding values of the exposed properties, in order to compare registered losses with expected ones. Building contents were not considered in this analysis because of the lack of specific and reliable information on their potential maximum damage values.

After that, new microscale functions were extrapolated using the following information on the 319 affected elements:

- building location;
- building typology;
- registered losses, as from damage forms provided by the municipality of Caldogno; as explained above, only building damage was considered;
- potential maximum damage value of the building, depending on its typology and size, expressed in terms of rebuilding value;
- damage factor, calculated by dividing the economic reported damage by the potential maximum damage for each building;
- registered water level: for buildings characterised by the presence of a basement, water depths on the street level were assumed for plotting depth–damage data, as for these typologies neither precise hydraulic information on water levels in the underground floor was available, nor it was possible to derive them from the hydraulic model.

Therefore, it was possible to describe the effect of inundation depths on walls, floors, doors, windows, plumbing and electrical systems, etc. associated with each single object by coupling the values of flood depth and damage factor.

Results and discussion

Damage modelling: mesoscale analysis

Direct flood loss estimates, based on the application of the various damage models, and the relative errors from the official damage information of 14.8 million Euro are given in Table 2, which demonstrates a large variability in the results, in the range of 4.6–68.2 million Euro, with minimum relative errors under ± 10% obtained with Standard Method, Damage Scanner and JRC-Switzerland functions. The largest spread in the results was found using JRC-UK and JRC-Denmark curves, whereas others gave relative errors in the range from ±20% to about 70%. These results are in line with similar studies in the literature regarding damage model validation in Europe: for example, Jongman *et al.* (2012) applied seven different models for two study areas, one in Germany and one in the UK, and found substantial uncertainty, calculating higher damages for the event characterised by lower observed damage; Apel *et al.* (2009) compared estimated damages derived from the application of some damage models with recorded losses after the 2002 Elbe flood, showing differences ranging from −87% to 34%; Thieken *et al.* (2008), in a validation study of FLEMOps model for two different flood events in Germany, found relative errors of the order of 20% and exceeding 1000% in a case, demonstrating that transferability of damage models is limited not only in space, but also in time.

Table 2 Mesoscale analysis: absolute values and relative errors of the estimates from the reported damage of 14.8 million Euro

Damage model	Estimated damage (M€)	Relative error (%)	Difference factor (–)
JRC-Belgium	≈11.4	−22.9	2.48
JRC-Czech Republic	≈6.9	−53.4	1.50
JRC-Denmark	≈68.2	+360.8	14.83
JRC-Germany	≈4.8	−67.6	1.04
JRC-Netherlands	≈4.6	−68.2	Min
JRC-Norway	≈22.2	+50.0	4.83
JRC-Switzerland	≈14.1	−4.7	3.07
JRC-UK	≈58.5	+295	12.72
Damage scanner	≈16.0	+8.1	3.48
Flemish model	≈9.3	−37	2.02
FLEMOps	≈11.5	−22.9	2.51
Hydrotec	≈22.0	+48.6	4.78
Rhine Atlas model	≈5.4	−63.5	1.17
Standard Method	≈14.3	−3.7	3.10

In addition, it is acknowledged that value and function uncertainty can have a significant influence on the output of damage modelling (Bubeck *et al.*, 2011; de Moel and Aerts, 2011; Jongman *et al.*, 2012). In this study, we focused on the second type of uncertainty, using unique maximum damage values and different curves, in order to isolate the single effect of model choice on simulated damages. A measure for function uncertainty is reported in Table 2, which shows the relative difference factors, calculated by dividing each estimate by the lowest one (JRC-Netherlands in this case): these values ranged from about 1.1 to 4.8 for most of the models and they reached 12.7 and 14.8 for JRC-UK and JRC-Denmark curves respectively.

The large uncertainty inherent to the application of the various damage models shown in Table 2 depends on the very different shapes of the damage curves. In fact, when comparing them, two observations become evident: the first one is that some curves (e.g. JRC-Denmark, JRC-UK) are steeper than others; and the second concerns the different assumption at which water level the maximum damage is reached (e.g. JRC-UK curve shows that a water level of approximately 1 m results in a 100% damage factor (Figure 5), whereas others do not reach a 100% damage factor even at 6 m).

This scatter in the results was also illustrated in other studies by de Moel and Aerts (2011) and Bubeck *et al.* (2011), who found that damage estimates calculated by means of Rhine Atlas, Damage Scanner and Flemish models can differ by a factor up to 4; Jongman *et al.* (2012) calculated a relative difference for function uncertainty of a factor of 3.7 and 10.5 for the German and the English case study respectively. The higher spread in our results can be explained by looking at the characteristics of the flood event and in particular at registered inundation depths, since function variability is particularly marked at low water levels: in fact, the histogram in Figure 3 shows a large share of grid cells inundated with low inundation depths, with an average level of about 0.8 m, which is considerably lower than those in the two cases of Jongman *et al.* (2012), equal to 1.8 m and 1.5 m.

In light of these findings, it can be a critical issue to choose a damage model from literature to be applied in a country with no data, like Italy. It is true that, in theory, more reliable results could be obtained by transferring damage models from related and comparable regions. But, at this point, a question remains on how to identify similar regions in terms of susceptibility to flood damage. In fact, except for rare cases, at the actual state of the art this operation can be no more than a guess, as no detailed information is usually provided on the limits of applicability of the models and on their explicative variables, e.g. building construction types and river basin and flood characteristics. For this reason, it would be desirable for future damage models to provide these additional data in order to have the possibility to explain the differences in the shapes of the damage curves for the various countries and then to enhance the reliability of their results when transferred to other contexts.

Therefore, given these large differences, mesoscale damage data for Caldogno were plotted and compared with the transferred curves (Figure 5). A linear regression was chosen for obtaining a new local depth–damage function (the solid red one in Figure 5) because of reasons of interpretation (Prettenthaler *et al.*, 2010) and because of the observation that most of literature curves can be well approximated by a straight line for water levels lower than 1.5 m. Considering the scatter in the underlying points, the correlation coefficient was rather low ($R^2 = 0.18$), but also the best fitting functions (power and polynomial) were characterised by R^2 values of about 0.26. In order to analyse the effect of this dispersion on damage estimates, the new curve was then applied to the 2010 inundation scenario, following the same procedure used for the other models: this resulted in an estimated loss of 14.2 million Euro, with a relative error of –4% from the registered damage. This low error gave no reason to prefer other functional forms over the simple linear one.

Damage modelling: microscale analysis

Table 3 summarises estimated damage calculated by using the selected microscale functions. These values ranged from about 6 to 12 million Euro, resulting in a maximum relative error from the reported building damage (7.4 million Euro) of about 82%, obtained with the curve of Dutta *et al.* (2003). If excluding the function of Luino *et al.* (2009), which overestimated the expected damage by more than 50%, the other models gave similar estimates, with errors in the order of 15–20%.

An interesting observation can arise from the analysis of the outputs of the Italian damage models. In particular, the synthetic ones produced comparable results with those obtained with the 'Caldogno curves', in contrast to those found with the empirical one; this result was probably

Table 3 Comparison between reported and estimated damages at the microscale (building damage only)

Building type	Reported building damage (M€)	Expected damage (M€)						
		Microscale damage model						
		Debo	Dutta	FLEMOps	Oliveri	Luino	Arrighi	Caldogno
Single-family detached (low quality)	1.35	1.33	2.47	1.18	1.21	2.05	1.49	0.99
Multifamily-multistorey	2.00	1.38	3.45	1.68	1.49	3.05	1.36	1.89
Semidetached	1.57	1.07	2.88	1.45	1.27	2.34	1.35	1.56
Single-family detached	2.50	2.18	4.70	2.44	2.12	3.88	2.31	2.24
Total	7.42	5.96	13.49	6.65	6.09	11.32	6.51	6.68
Relative error (%)		–19.7	+81.8	–10.0	–17.9	+52.6	–12.1	–10.0
Difference factor (–)		Min	2.26	1.11	1.02	1.90	1.09	1.12

related to the nature of the curve of Luino *et al.* (2009), which was derived from an ex-post analysis in a mountainous basin, with different flood event characteristics, confirming that the transferability of damage models should be limited to similar regions, in order to obtain reliable loss estimates (Cammerer *et al.*, 2013).

Looking at function uncertainty, difference factors, defined as in the mesoscale analysis, were calculated based on the outcomes of the models: the results in Table 3 reveal similar values of about 1.1 for most of the functions, reaching a factor of about 2 for the models of Dutta *et al.* (2003) and Luino *et al.* (2009), lower than those found in the mesoscale analysis.

Regarding the construction of new functions, data sets related to the 319 damaged buildings are displayed in Figure 6(a), showing a large scatter. After that, it was analysed if this great variability could be reduced by taking into account building vulnerability: data points were then extracted for the different building types, resulting in the plots of Figure 6(b) and (c).

Different function forms were examined but, even for the best fitting ones, the correlation coefficient R^2 remained below 0.3; in addition, some fits resulted in not physically acceptable descending functions.

Therefore, even though most of the published microscale functions show different shapes, a linear regression for relating water level and damage factor was preferred due to the difficulties in giving a physical explanation to other fits (Prettenthaler *et al.*, 2010). It is clear that the production of damage curves necessarily implies a considerable smoothing of the data, as the scatter at the microscale is usually considerable (Smith, 1994). But this operation should be supported by a physical description of the effects of water on building components: for this reason, a future development of these functions could involve the combination of the mere empirical analysis of the raw damage data with synthetic approaches (i.e. 'what-if analyses'), which could give valuable insights for obtaining a more comprehensive representation of the damage mechanisms and, consequently, more reliable models.

In each category, a distinction was made between elements with and without basement, in order to determine two different curves for each sub-data set. Table 4 compares the flood depths on the street level necessary for causing a damage factor equal to 0.1 for the different building types, according to the regression lines represented in Figure 6; similar values, in the range of 0.75 m, were found for all 'no basement' elements and they decreased to about 0.35 m for 'with basement' structures, mainly due to a larger residence time of water and to the 'filling effect' occurring in basements.

Following the same procedure used with the other functions, the new curves were then applied at the microscale to the inundation scenario, in order to measure the influence of the simplifying assumption of using a linear regression on damage estimates. As shown in Table 3, modelled damage amounted to 6.7 million Euro, meaning a relative difference of −10% from the reported loss (7.4 million Euro), which was slightly higher than the −4% obtained in the previous section with the application of the new mesoscale curve. A similar result was also found by Apel *et al.* (2009), who showed that mesoscale models can outperform microscale and more detailed ones, especially in cases of small inundated areas with few affected objects (Merz *et al.*, 2004).

Table 4 Flood depths on the street level necessary for causing a damage factor equal to 0.1, according to the regression lines obtained for the different building types

Building type	With basement (m)	No basement (m)
Multifamily-multistorey	0.348	0.746
Single-family detached ('villas')	0.321	0.807
Single-family detached (lower quality)	–	0.769
Semidetached	0.434	0.714

Conclusions

Despite the growing importance that damage modelling is gaining in flood risk management, it can be still considered a relatively new research area, if compared with other water resources fields, as hydrologic and hydraulic modelling, and thus affected by a large uncertainty, mainly related to the quality of depth–damage curves.

In this paper, detailed postflood damage data were first used to perform a validation of existing curves in the literature, with uncertainty analysis. It was demonstrated that the transferability in space of damage models is limited because of the large variability in the outputs, with relative errors of the estimates from the reported loss ranging from 5% to 360%, resulting in relative difference factors for function uncertainty from 1.1 to 14.8 for mesoscale models, diminishing to about 1.1–2.2 for the considered microscale ones. This confirms that caution in transferring and applying damage curves from one country to another should always be used, as transferability depends on (but it is not limited to) the similarity, in terms of flood event and/or building characteristics, between the two countries or regions. However, especially for mesoscale curves, the lack of detailed information on hazard and vulnerability sides can be seen as an obstacle for identifying the conditions of applicability of the models to other contexts. In the absence of these requirements, the application of alternative models is suggested, with the aim of determining a range of possible damage estimates for a more rational decision-making.

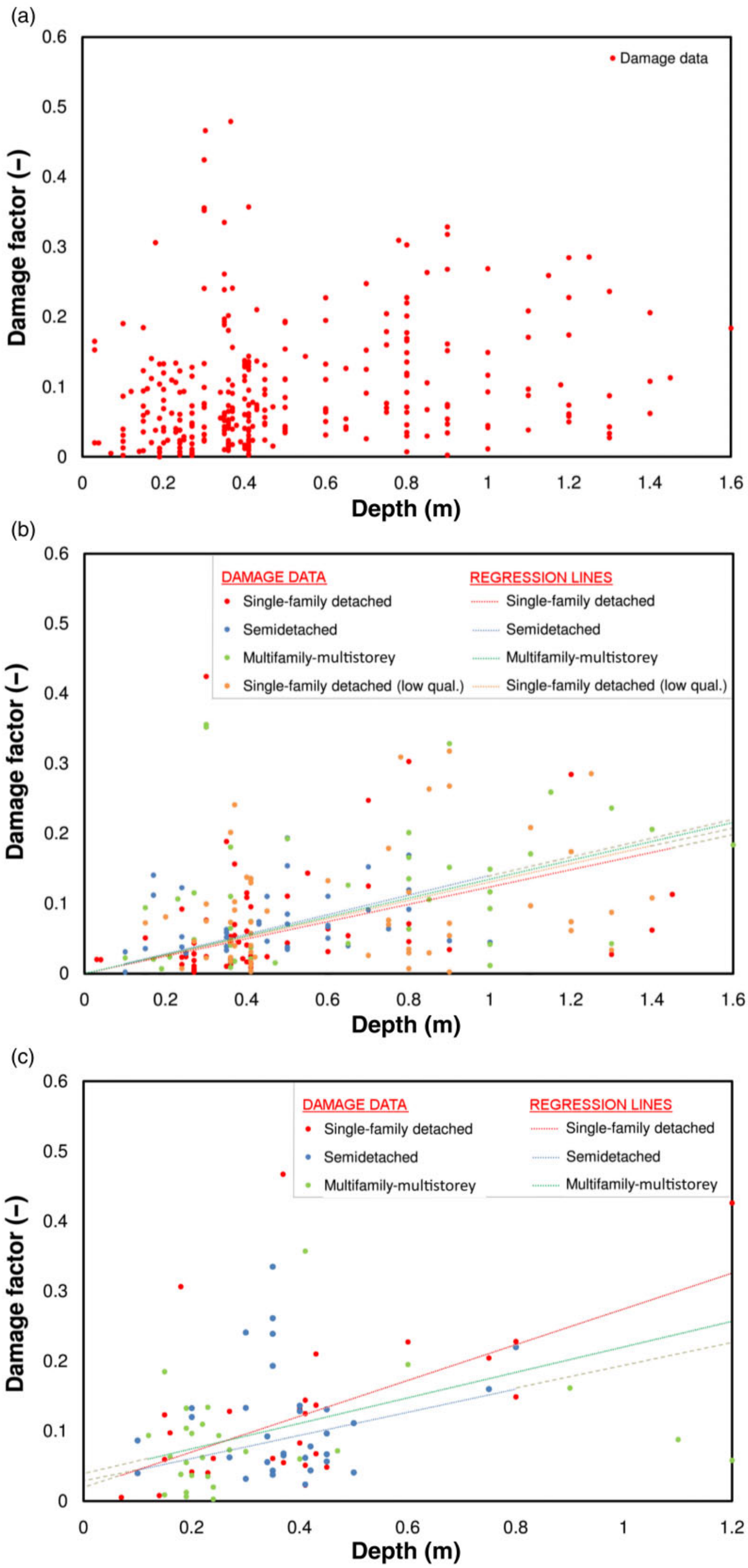

Figure 6 Microscale analysis for the residential sector: (a) damage data from the 2010 Bacchiglione flood; (b) regression lines for buildings without basement; (c) regression lines for buildings with basement. Continuous buildings were excluded due to limited recorded data.

Given this scenario, new insights were given for the development of local residential depth–damage curves, both at meso- and microscale, under the simplifying assumption of a linear relationship between water depth and damage factors. These empirical functions can form the basis for a future development of a damage model, combined with a synthetic approach, which could give a more comprehensive description of damage mechanisms.

The new curves from the ex-post analysis were then applied to the inundated area, revealing a better performance of the mesoscale model compared with the more detailed microscale one, probably due to the small extent of the inundated area, with few affected objects.

However, because the analysis performed in this paper was limited to a case study, further test cases in other Italian regions should be undertaken in order to support a more general applicability of the results, emphasising the necessity of a systematic collection of postflood damage data for the development of thorough standardised methods.

References

Apel H., Thieken A., Merz B. & Bloschl G. Flood risk assessment and associated uncertainty. *Nat Hazard Earth Syst Sci* 2004, **4**, (2), 295–308.

Apel H., Aronica G.T., Kreibich H. & Thieken A. Flood risk analyses – how detailed do we need to be? *Nat Hazards* 2009, **49**, (1), 79–98.

Arrighi C., Brugioni M., Castelli F., Franceschini S. & Mazzanti B. Urban micro-scale flood risk estimation with parsimonious hydraulic modelling and census data. *Nat Hazard Earth Syst Sci* 2013, **13**, 1375–1391.

ARPAV. Scheda evento 'Pluvio': 31 Ottobre – 02 Novembre 2010, 2010.

Beta Studio. Interventi per la sicurezza idraulica dell'area metropolitana di Vicenza: bacino di laminazione lungo il Torrente Timonchio in comune di Caldogno – Progetto definitivo. Relazione idrologica e idraulica, 2012.

Bubeck P., de Moel H., Bouwer L.M. & Aerts J.C.J.H. How reliable are projections of future flood damage? *Nat Hazards Earth Syst Sci* 2011, **11**, 3293–3306.

Cammerer H., Thieken A.H. & Lammel J. Adaptability and transferability of flood loss functions in residential areas. *Nat Hazard Earth Syst Sci* 2013, **13**, 3063–3081.

Debo N.T. Urban flood damage estimating curves. *J Hydraulics Div* 1982, **108**, (10), 1059–1069.

DEFRA. The appraisal of human related intangible impacts of flooding. R&D Technical Report FD2005/TR, 2005.

Downton M.W. & Pielke R.A. How accurate are disaster loss data? The case of U.S. flood damage. *Nat Hazards* 2005, **35**, 211–228.

Dung N.V., Merz B., Bardossy A., Thang T.D. & Apel H. Multi-objective automatic calibration of hydrodynamic models utilizing inundation maps and gauge data. *Nat Hazard Earth Syst Sci* 2011, **15**, 1339–1354.

Dutta D., Herath S. & Musiake K. A mathematical model for flood loss estimation. *J Hydrol* 2003, **277**, 24–49.

EEA. Mapping the impacts of natural hazards and technological accidents in Europe – an overview of the last decade. EEA Technical Report 13/2010, 2010.

European Commission. EU directive on the estimation and management of flood risks (EU/60/2007), 2007.

Freni G., La Loggia G. & Notaro V. Uncertainty in urban flood damage assessment due to urban drainage modelling and depth–damage curve estimation. *Water Sci Technol* 2010, **61**, 2979–2993.

Genovese E. A methodological approach to land use-based flood damage assessment in urban areas: Prague case study. JRC Report – EUR 22497, 2006.

Giang N.T., Cheng J. & Phoung T.A. A method to construct flood damage map with an application to Huong River basin, in Central Vietnam. *VNU J Sci Earth Sci* 2009, **25**, 10–19.

HKV Consultants. Flood damage functions for EU member states. Final Report for JRC – Institute for Environment and Sustainability, 2007.

Hydrotec. Hochwasser-Aktionsplan Angerbach. Teil I: Berichte und Anlagen. Studie im Auftrag des Stua Dusseldorf, Aachen, Germany, 2001.

ICPR. *Atlas on the risk of flooding and potential damage due to extreme floods of the Rhine*. Koblenz: International Commission for the Protection of the Rhine, 2001.

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

Jonkman S.N., Bockarjova M., Kok M. & Bernardini P. Integrated hydrodynamic and economic modelling of flood damage in the Netherlands. *Ecol Econ* 2008, **66**, 77–90.

Klijn F., Baan P., De Bruijn K.M. & Kwadijk J. Overstromingsrisico's in Nederland in een veranderend klimaat: verwachtingen, schattingen en berekeningen voor het project Nederland Later, WL Delft Hydraulics Report Q4290.00, 2007.

Kok M., Huizinga H.J., Vrouwenvelder A.C.W.M. & Barendregt A. Standaardmethode2004 Schade en Slachtoffers als gevolg van overstromingen, DWW-2005-005, 2005.

Kourgialas N.N. & Karatzas G.P. A hydro-economic modelling framework for flood damage estimation and the role of riparian vegetation. *Hydrol Process* 2013, **27**, 515–531.

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

Kreibich H., Seifert I., Merz B. & Thieken A.H. Development of FLEMOcs – a new model for the estimation of flood losses in the commercial sector. *Hydrol Sci J* 2010, **55**, (8), 1302–1314.

Luino F., Cirio C., Biddoccu M., Agangi A., Giulietto W., Godone F. & Nigrelli G. Application of a model to the evaluation of flood damage. *Geoinformatica* 2009, **13**, 339–353.
Merz B. & Thieken A.H. Flood risk curves and uncertainty bounds. *Nat Hazards* 2009, **51**, 437–458.
Merz B., Kreibich H., Thieken A. & Schmidtke R. Estimation uncertainty of direct monetary flood damage to buildings. *Nat Hazards Earth Syst Sci* 2004, **4**, (1), 153–163.
Merz B., Kreibich H., Schwarze R. & Thieken A. Assessment of economic flood damage. *Nat Hazards Earth Syst Sci* 2010, **10**, 1697–1724.
Messner F., Pennning Rowsell E.C., Green C., Meyer V., Tunstall S.M. & Van der Veen A. Evaluating flood damages: guidance and recommendations on principles and methods, FLOODsite, Report No. T09-06-01, 2007.
Meyer V., Priest S. & Kuhlicke C. Economic evaluation of structural and non-structural flood risk management measures: examples from the Mulde River. *Nat Hazards* 2012, **62**, 301–324.
Meyer V., Becker N., Markantonis V., Schwarze R., van den Bergh J.C.J.M., Bouwer L.M., Bubeck P., Ciavola P., Genovese E., Green C., Hallegatte S., Kreibich H., Lequeux Q., Logar I., Papyrakis E., Pfurtscheller C., Poussin J., Przyluski V., Thieken A.H. & Viavattene C. Assessing the costs of natural hazards – state of the art and knowledge gaps. *Nat Hazards Earth Syst Sci* 2013, **13**, 1351–1373.
de Moel H. & Aerts J.C.J.H. Effect of uncertainty in land use, damage models and inundation depth on flood damage estimates. *Nat Hazards* 2011, **58**, 407–425.
Molinari D., Menoni S., Aronica G.T., Ballio F., Berni N., Pandolfo C., Stelluti M. & Minucci G. Ex post damage assessment: an Italian experience. *Nat Hazards Earth Syst Sci* 2014, **14**, 901–916.
NR&M (Department of Natural Resources and Mines, Queensland Government). Guidance on the assessment of tangible flood damages, 2002.
Oliveri E. & Santoro M. Estimation of urban structural flood damages: the case study of Palermo. *Urban Water* 2000, **2**, 223–234.
Penning-Rowsell E., Viavattene C., Pardoe J., Chatterton J., Parker D. & Morris J. *The benefits of flood and coastal risk management: a handbook of assessment techniques*. London: Flood Hazard Research Centre, Middlesex University, 2010.
Plate E.J. Flood risk and flood management. *J Hydrol* 2002, **267**, 2–11.
Prettenthaler F., Amrusch P. & Habsburg-Lothringen C. Estimation of an absolute flood damage curve based on an Austrian case study under a dam breach scenario. *Nat Hazards Earth Syst Sci* 2010, **10**, (4), 881–894.
Regione del Veneto. Banca dati della Copertura del Suolo della Regione Veneto, 2009.
Regione del Veneto. Veneto. La grande alluvione, 2011.
Sayers P.B., Hall J.W. & Meadowcroft I.C. Towards risk-based flood hazard management in the UK. *Civil Eng* 2002, **150**, (5), 36–42.
Scawthorn C., Flores P., Blais N., Seligson H., Tate E., Chang S., Miffin E., Thomas W., Murphy J., Jones C. & Lawrence M. HAZUS-MH Flood loss estimation methodology. II. Damage and loss assessment. *Nat Hazards Rev* 2006, **7**, (2), 72–81.
Smith D.I. Flood damage estimation – a review of urban stage–damage curves and loss functions. *Water SA* 1994, **20**, (3), 231–238.
Smith K. & Ward R. *Floods: physical processes and human impacts*. Chichester: John Wiley and Sons, 1998.
Thieken A.H., Muller M., Kreibich H. & Merz B. Flood damage and influencing factors: new insights from the August 2002 flood in Germany. *Water Resour Res* 2005, **41**, (12), W12430.
Thieken A.H., Olschewski A., Kreibich H., Kobsch S. & 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 I*. Southampton, UK: WIT Press, 2008, pp. 315–324.
USACE. Catalog of residential depth–damage functions used by the Army Corps of Engineers in flood damage estimations. IWR Report 92-R-3, 1992.
Vanneuville W., Maddens R., Collard C., Bogaert P., de Meyer P. & Antrop M. Impact op mens en economie t.g.v. overstromingen bekeken in het licht van wijzigende hydraulische condities, omgevingsfactoren en klimatologische omstandigheden. MIRA/2006/02, Universiteit Gent, Belgium, 2006.
Vorogushyn S., Lindenschmidt K.E., Kreibich H., Apel H. & Merz B. Analysis of a detention basin impact on dike failure probabilities and flood risk for a channel–dike–floodplain system along the river Elbe, Germany. *J Hydrol* 2012, **436–437**, 120–131.