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PROPAGATION OF HYDRAULIC MODELLING UNCERTAINTY ON DAMAGE ESTIMATES

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ABSTRACT: This work focuses on the impact of strategies used to model and map flood hazard in damage estimations. We consider different strategies to model the flood phenomenon, as a function of: (1) the type of hydraulic model used – 1D, hybrid 1D/2D or 2D software, i.e. model selection; and (2) the simplifications made by the modeller when representing the topography and bathymetry of the river system, i.e. parametric choices. With this purpose, different hazard models and damage estimations were realised in the town of Fislis, in eastern France. Hec-RAS, Mike 21 and Mike Flood hydraulic models were used in order to measure the selection of model effects. We considered different scale of analysis (level of details) when constructing the different modelling scenarios – density of cross-sections and hydraulic structures (1D models), and the digital elevation model cell resolution (2D models). Thirty-two models were used to simulate floods with different return-periods. The 2D models tended to overestimate the flood surfaces and the 1D models tended to overestimate floodwater depths. The results of uncertainty propagation tests on damage estimations revealed that the choice of the scale of analysis was the mainly uncertainty influencing aspect of the evaluation. These parametric choices were responsible for 75% of global uncertainty, against 18% for model selection. Furthermore, we notice that the increase of the precision of hazard modelling has different impacts on flood maps and damage estimations, according to the type of model. For 1D models, the more detailed the models are (higher density of cross-sections), the higher damage estimation results are. For 2D models, the more the models are precise (small grid-cells) the lower damage estimates are. The results of damage estimations are strongly influenced by hydraulic modelling choices, therefore the production of flood maps for this purpose should be deeply analysed.

Key Words: Flood damage, Flood loss, Flood map, Vulnerability analysis.

1. INTRODUCTION

Flood hazard maps are the main base for flood control and flood management studies (NRC, 2009). Former flood hazard maps as well as hypothetical flood maps for different probabilities of occurrence and flood risk maps are powerful tools improving the understanding of the flood phenomenon and its related risks (de Moel et al., 2009). Several numerical models were developed during the last decades for simulating floods. Some frequently used models used to simulate floods are: Hec-RAS, Mike Flood, Sobek, ISIS of Wallingford software, Telemac 2D and Lisflood (Stelling and Verwey, 2005; Büchele et al., 2006; Di Baldassarre et al., 2009; Dutta et al., 2003; Finaud-Guyot, 2009; Horritt and Bates, 2002). Advances in computational engineering and the increased availability of detailed data for modelling purposes allowed great improvement on this science (Woodhead, 2007). Nowadays numerical techniques have matured, providing robustness and efficiency in model simulation (Stelling and Verwey, 2005; Crossley, 1999). Geographic information system (GIS) and raster-based models are also available for modelling floods (Bates and De Roo, 2000; Chen et al., 2009). Data requirements vary from one model to another, according to the approach used, scheme simplifications and model interface (Data requirements are generally specified in software user's manuals). The basic data required by flood inundation models is composed of: (1) topographic data for the hydraulic model computational grid and the inundation maps; (2) boundary conditions at the downstream and upstream ends of the model domain; (3) effective friction values (roughness coefficients); and (4) model calibration/ validation data.

In practical applications, several criteria influence the strategic choices to model floods and produce hazard maps. The scale of the analysis is a fundamental criterion, as well as data and resources availability for the study. However, this choice is still vague (NRC, 2009). In the case of the EU Flood Directive, the national analysis of the flood risk is a difficult challenge once national and local scale models are to developed in order to map flood hazard as well as the flood risk. In spite that potential flood damage estimates becomes an important tool for flood management purposes, the impact of flood hazard mapping on flood damage evaluations are not yet deeply analysed in literature. Few studies propagate flood hazard uncertainties into damage estimations (Chen et al., 2004; Apel et al., 2008b; Merz and Thieken, 2009; Apel et al., 2008a). These studies revealed that this uncertainty might represent a big part of global uncertainty of flood damage estimates.

Several uncertainty sources can influence the accuracy of flood maps (Bales and Wagner, 2009). As described by NRC (2000), uncertainty in flood maps can generate several losses in terms of flood management. Better understanding on the flood phenomenon and its related uncertainties is required to guide decision-making processes. Some examples of uncertainty sources are: hydrologic data; topographic/bathymetric data; land-use data and roughness coefficient estimation; models initial condition determination; models calibration, etc. The kind of hydraulic model that should be used for different purposes represent another important source of uncertainties (NRC, 2009). The most appropriate flood study method to be used for a particular map depends on the accuracy of the topographic data and the overall flood risk, including flood probability, defined vulnerabilities, and consequences (NRC , 2009). The FEMA guidelines for flood hazard mapping (FEMA, 2003) highlights the limitations of several models but do little to help in the determination of which type of models are most appropriate for a given situation (NRC , 2009).

The construction of hydraulic models involves several choices in order to represent the rivers system. Different levels of details can be used during these analyses. The major difference is the amount of information used in the study process. The scale of the analysis plays an important role on the determination of the methods and levels of accuracy to consider. Uncertainty is linked to the amount of data used as well as how modellers process this data, *i.e.* human-factor behind modelling processes. Few studies analysed these aspects. Cook and Merwade (2009) measured how flood maps are influenced by the type of model used, and by the different topographic data and geometry simplifications made when building flood scenarios. Other studies analysed the effect of grid/mesh resolution on flood modelling (Golding, 2009; Horritt and Bates, 2001b). They highlight that these considerations can also considerably affect flood extent predictions.

The main objective of the present work is to quantify the impact of hydraulic modelling choices on flood damage estimations. The selection of the hydrodynamic software and the scale-induced simplifications are the core of this work. Indeed, we compare several strategies used to map riverine flooding based on these aspects, and we measure the variability of damage estimates as a function of these different aspects. In the second part of this work, we present the case study and the methods, datasets and scale-considerations used in the construction of the different modelling scenarios. Finally, in the last section, we measure the results of the simulations in terms variability of damage estimates according to the different flood modelling strategies.

2. METHOD

In order to measure the impact of the selection of hydraulic models and parametric uncertainties on damage estimations, we proceed as follows. Firstly, different strategies were used to model floods and produce flood hazard maps for one specific site. Secondly, the flood maps produced were used to estimate flood damage. Finally, we measure the variability of damage estimates induced by the different hydraulic modelling uncertainty sources. These steps are presented in the following sections, after a general overview of the dataset used to construct the different hydraulic modelling strategies.

2.1 Case study and datasets used for the simulations

The comparison of flood modelling strategies realised in this work is based on a real case study: the town of Fislis, in eastern France. The Fislis town is crossed by the Ill River and an affluent, Limendenbach stream (Figure 1). The river geometry, the hydraulic structures and the proximity of buildings to the river contribute to the recurrent flooding of dwellings.

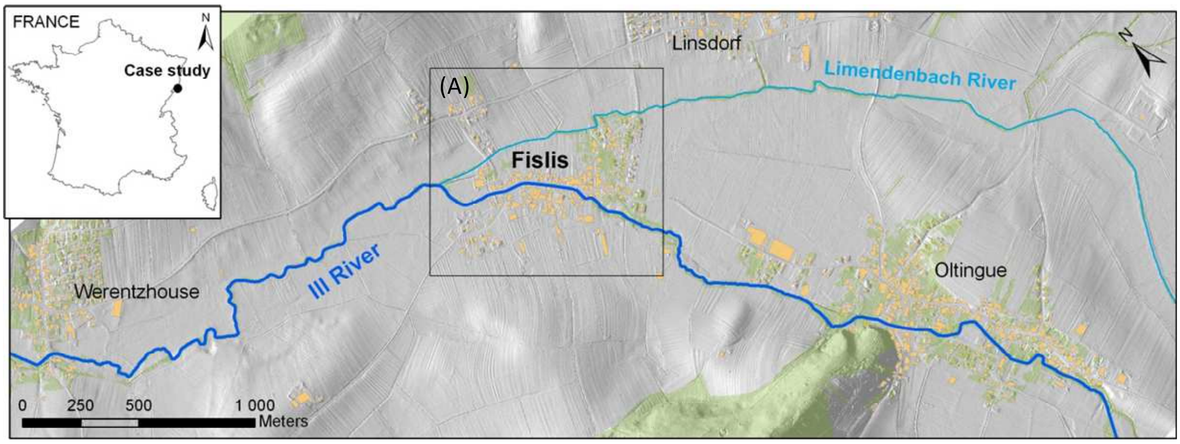

Figure 1: Study area: the town of Fislis, in Alsace, France.

A hydraulic model constructed by the French institution "Conseil Général du Haut Rhin" with HEC-RAS software was used as a starting point for the construction of the different flood modelling scenarios developed in this study. Topographic data used in this study was issue of a digital elevation model (DEM) produced with Light detection and Ranging (LIDAR) technology in 2008, with 0.2 vertical and 0.5 horizontal precision. Data relative to the rivers bathymetry, roughness coefficients and hydraulic structures (singularities) was obtained through field measurements realized in 2010. This data accounted 23 hydraulic structures for the 6.1 km of the Ill River in analysis and 5 hydraulic structures for the 4.1 km of the Limendenbach River. Hydrological analyses were realised with the Gumbel distribution method for a series of 30 years gauged data (Hydrological data from 1978 to 2008 in the hydrometric station of Altkirch (Ill river) - internet site: "Banque hydro" http://www.hydro.eaufrance.fr/). Regional regression based on the surface of the watershed was realised for obtaining the following discharge-frequency relationships (Figure 2). Finally, the satellite images-based land-use dataset named BD OCS, distinguishing 94 classes of land-uses on the scale of 1: 25000, was used for the development of floodplain roughness-coefficient maps, with Manning-Strickler values. These datasets were used for the different modelling scenarios developed hereafter.

2.2 Differences between modelling scenarios

The hazard modelling strategies developed here are different in relation to two aspects: (1) the type of hydrodynamic approach (1D, 1D/2D and 2D computational programs) used to simulate flood events, *i.e.* model selection; and (2) the density of data processed when representing the geometry, bathymetry and topography (cross-sections for 1D and 1D/2D models and grid resolution for 1D/2D and 2D models) of the studied system, *i.e.* model parametric choices.

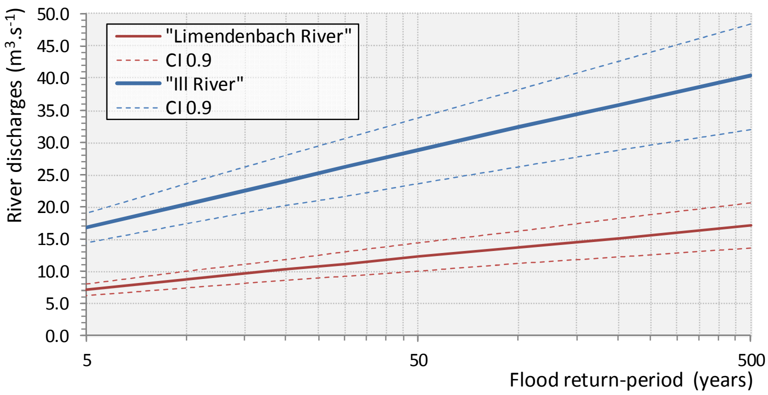

Figure 2: Estimated discharge/frequency values for the Ill River and its tributary Limendenbach at their confluence point.

2.2.1 Type of hydraulic model

In practical modelling processes, the selection of models is often based on the required engineering staff time for model development, overall consultancy time for product delivery, speed of computation, accuracy level of results, data requirements, numerical robustness, user-interface of the software, etc (Stelling and Verwey, 2005). Indeed, the cost of flood modelling and mapping can be consequent and then influence the selection of models and methods to use as well as the quality/quantity of data to use (NRC , 2009). Indeed some efforts were done to guide modeller on the selection of models (FEMA, 2003), this selection is still vague (NRC, 2009). In this study, three hydrodynamic models largely employed all over the world for flood analysis were used to build the different scenarios of flood simulations (Table 1). These models are based on different hypothesis and they offer different possibilities for the end-user to simulate floods.

Table 1: Description of the main characteristics of the models used to simulate floods.

Approach	Model	Physical laws	Numerical methods
1D	HEC-RAS software (v. 4.1) by the U.S. Army Corps of Engineers[a] (HEC, 2010).	Bernoulli energy equation (steady-state flow); Saint-Venant shallow water equations (unsteady-state flow)	Algebraic equation (steady-state flow); FDM (unsteady-state flow)
2D	Mike 21 software by DHI Group[b]	2D Saint-Venant shallow water equations (steady/unsteady state flow)	FVM (steady/unsteady state flow)
Hybrid 1D/2D	Mike Flood software developed by DHI Group[b]	1D and 2D Saint-Venant shallow water equations (steady/unsteady state flow)	FDM (steady/unsteady state flow)

[a] Hydrologic Engineering Center River Analysis System web site: http://www.hec.usace.army.mil/software/hec-ras
Water resources MIKE by DHI products web site: http://www.mikebydhi.com/Products/WaterResources

2.2.2 Geometric representation of the river systems

All three models require geometrical datasets, although they use them in different ways. The type of model and the scale of analysis play an important role on the model parametric choices. In 1D models, the amount of hydraulic structures and cross-sections to consider in the analysis is influenced by the size of the area due to resources constraints. For 2D models, the modeller is constraint to rescale topographic data in order to respond to model requirements. Even thought great improvement was done on the quality of topographic data, the models numerical limitations and simulation time requirements induce to downscaling methods. Therefore, the level of detail on the description of the floodplain topography (resolution of the grid/mesh cell) also depends on the size of the study area. We constructed 32 flood models considering different geometric representation of the case study for the three hydraulic approaches used here (Table 2).

Table 2: Differences between the modelling scenarios built with different hydraulic models.

Approach	Nb. of scenarios	Differences between scenarios
1D	12	Number/position of cross-sections and number of hydraulic structures
2D	5	Size of the interpolated grid cells
Hybrid 1D/2D	15	1D part - Number of cross sections and hydraulic structures 2D part - Interpolated grid cell size

The density of cross-sections and hydraulic structures modelled in 1D models as well as the size of the interpolated grid cells in 2D models were both based on scale-based assumptions, making reference to the model expected level of detail (Messner et al., 2007). When using the 1D approach (HEC-RAS), we distinguished three scales of analysis: “micro”, “meso” and “macro”, from which the micro-scale is the more detail one. Four micro-scale (high-density data) scenarios were built considering different emplacements for cross-sections (scenarios A-D in Figure 3). The same consideration was made for constructing four meso-scale (medium-density data) scenarios (scenarios E-H in Figure 3) and four macro-scale (low-density data) scenarios (scenarios I-L in Figure 3). HEC-GeoRAS® v. 4.3 software and the Geographic Information System (GIS) ArcGIS v. 9.2 by ESRI were used to construct these different models.

The 2D modelling scenarios were based on the available digital elevation model (DEM). In order to improve the accuracy of bathymetric data for 2D simulations, the GIS-based method proposed by Merwade et al. (2008a) was used to interpolate the river main channel using field measurements. The DEM was processed using the ArcGIS v. 9.2 abd its Spatial and 3D Analyst extensions. All the 2D models constructed were based on regular rectangular grid cells representing the rivers bathymetry and the floodplain topography. The scale-considerations used to construct the 2D modelling scenarios concern the size of the interpolated grid cells used in the models. Five scenarios were built considering different levels of detail (grid cell sizes): the DEM was downscaled to 2m, 3m, 4m, 6m and 10m grid cell sizes – scenarios named M21_02, M21_03, M21_04, M21_06 and M21_10. For the construction of hybrid 1D/2D models we also considered three levels of detail (micro, meso and macro) for the 1D part of the model (river channels) (Figure 4).

Five scenarios were built for each of the different 1D scales of analysis used, using the Mike11 GIS software. These scenarios were different in relation the size of the interpolated grid cell used for the 2D part of the model (floodplain). The five scenarios built considering the 1D micro-scale (high-density data) used the DEM downscaled to 3, 4, 6, 10 and 15 meters grid cell resolution (scenarios MF_micro03, MF_micro04, MF_micro10 and MF_micro15). The 1D meso-scale (medium-density data) used 4, 6, 10, 15 and 20 meters grid cells (scenarios MF_meso04, MF_meso06, MF_meso10, MF_meso15 and MF_meso20) and the five 1D macro-scale (low-density data) scenarios used 6, 10, 15, 20 and 25 meters resolution (scenarios MF_macro06, MF_macro10, MF_macro15, MF_macro20 and MF_macro25).

2.1 Flood modeling, hazard mapping and damage estimation

Discharge/water depth relationships were used as boundary conditions downstream and upstream the model (determined using the reference model). In order to avoid boundary condition influences, the section of the reach considered for the construction of the different modelling scenarios was much longer than the area of interest (area A in Figure 1). Once adequate calibration data is seldom available for inundation models, the different modelling scenarios here were calibrated by using measurements at a single point which is the normal practice (Horritt and Bates, 2002; Bales and Wagner, 2009). Finally, we performed, for each modelling scenario, steady-flow simulations for eight hypothetical flood events: 5, 10, 20, 30, 50, 100, 200 and 500-yr return-period flood events (Figure 2). The HEC-RAS Mapper Floodplain Delineation Capabilities (HEC, 2010) was used to construct flood hazard maps issues of the HEC-RAS

1D simulations. The available DEM was used for the interpolation of the calculated flood-stages. We used ArcGIS 9.2 to process the results of the simulations performed with Mike 21 (2D) and Mike Flood (hybrid 1D/2D) software.

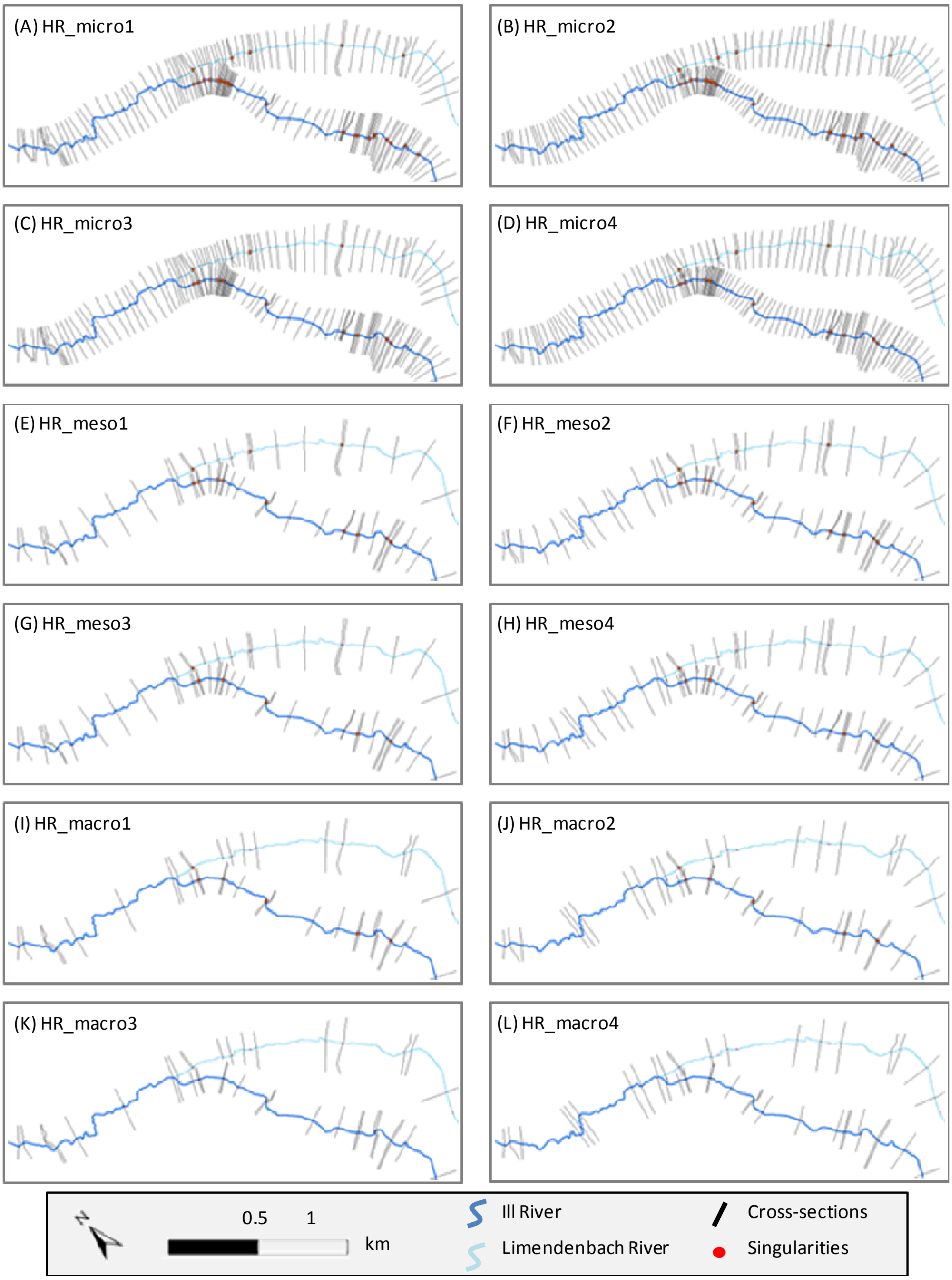

Figure 3: Topology of the 1D modelling scenarios built with HEC-RAS.

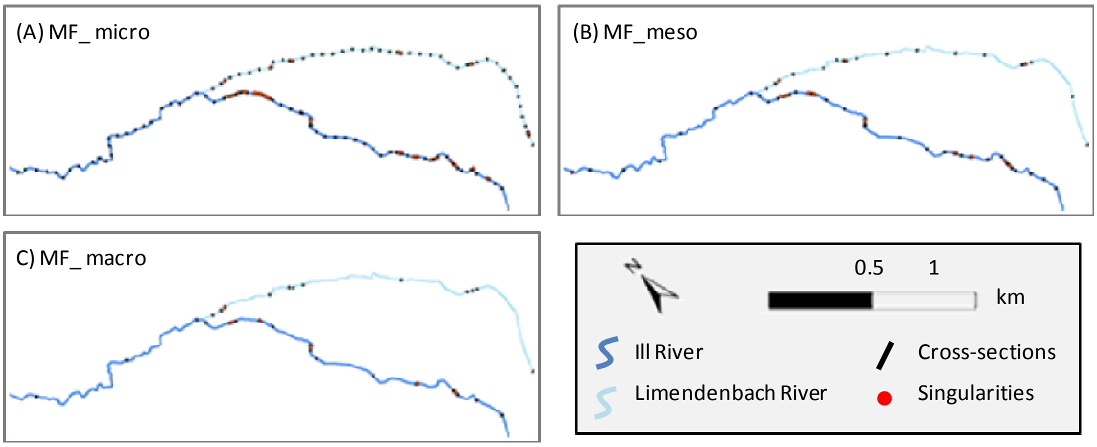

Figure 4: Geometry of the 1D part of the hybrid 1D/2D modelling scenarios.

All the flood maps were generated for the town of Fislis: the sub-area of 0.94 km^2 (area A in 0) was used for all the comparisons presented in the results of this work. The damage estimation realized on this work concerns only buildings and contents direct damage potential to floods. The damage model used establishes damage potential as a function of the types of buildings, their surfaces and the water depth inside buildings. Seventeen damage functions for residential (Torterotot, 1993) and commercial (DNRM, 2002) buildings were used to evaluate buildings damage-potential. Building vulnerability data was obtained through the analysis of available GIS datasets and detailed field-surveys. We analysed 231 buildings, classified according 17 vulnerability classes. The field surveys were realised at the elementary scale (building per building), in order to determine the typology of buildings, their construction characteristics and their ground floor elevation. The F.R.A.GIS GIS-based model (Eleutério et al., 2010) was used to combine hazard with vulnerability data, calculate flood damage, produce flood risk maps.

3. RESULTS

Flood maps produced within this work were compared and presented in the work of Eleutério and Mosé (2011). In it, the comparison of thirty-two 100-years flood maps produced using different models and scale-considerations revealed that: the selection of the type of model is the most important factor when considering the variability of flood maps parameters (water depth distributions);the scale of analysis is the most important uncertainty source for the determination of the surface of flood maps; the choice of the DEM resolution strongly influenced the results of the modelling processes.

Based on those maps, we realised 256 damage estimations, one for each of the eight flood-return period considered by the thirty-two modelling scenarios analysed in this work. These estimates are represented in thirty-two risk-curves (damage potential estimate vs. probability of occurrence), one for each hazard modelling scenario (Figure 5). In this figure, we highlight the best estimates for each model approach (1D; full 2D and hybrid 1D/2D). These were considered best estimates in relation to the similarity of 10, 30 and 100-yr flood extent maps produced with these scenarios in relation to the reference model used in this work. The estimates using the best 2D modelling scenario were higher than the estimates obtained through 1D and hybrid 1D/2D models. When comparing 1D with 1D/2D estimates, we notice that the estimations using the 1D best method result on greater damage values for flood return-periods shorter than or equal to 30 years. However, these estimations were quite similar. The risk curves above revealed that the uncertainty generated by parametric choices generated higher variability of estimates than the uncertainty generated by the selection of the models. The variability of 2D models showed to tend to the overestimation of damage estimates. The same tendency is observed for hybrid 1D/2D models, for which we notice great overestimation, especially on frequent events (lower than 50-yr return-periods). The variability of 1D based estimations is more homogeneous in relation to the best estimates.

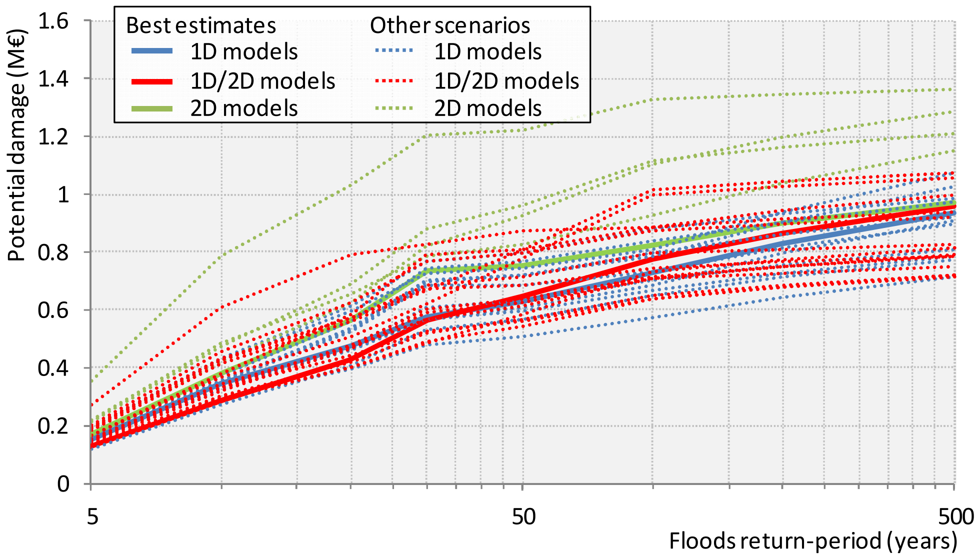

Figure 5: Risk curves (damage vs. probability) built using the different modelling scenarios.

In order to evaluate the global impact of different sources of uncertainty on the different evaluations we used these risk curves to calculate Expected Annual Damage (EAD) by summing up the "damage x frequency" values. These results are presented in the following graphs (Figure 6 and Figure 7).

The scale-considerations in the HEC-RAS modelling scenarios revealed that damage estimates increased when we improved the level of details on the hydraulic modelling process (*cf.* differences between 1D micro, meso and macro scales in Figure 6). In "micro" scale analyses, we were able to better appreciate low points along the channel, inducing more frequent inundations on the floodplain (larger flood surfaces). EAD were estimated at respectively 70, 80, 92 k€.year^{-1} for respectively macro, meso and micro scenarios, in average. We can make the same conclusions when comparing the scale-considerations for the 1D part of the hybrid models, (*cf.* differences between Mike Flood micro, meso and macro scenarios considering the same grid cell sizes for the 2D part of the model Figure 6). For example, EAD calculated with the Mike Flood 10m grid resolution vary from 76.5 k€.year^{-1} (1D macro scale), 86.8 k€.year^{-1} (1D meso scale), and 94.8 k€.year^{-1} (1D micro scale).

Expected annual damage (EAD) best estimates (based on best surface estimations) were 71.4 k€.year^{-1} using Mike Flood, 77.9 k€.year^{-1} using Hec-RAS and 89.7 k€.year^{-1} using Mike 21. When considering total variability (scale effect) the minimum EAD value was estimated at 64.8 k€.year^{-1} and the maximum at 163.8 k€.year^{-1} (more than 2.5 times the minimum estimate. These results presented in Figure 6 highlight that scale considerations relative to the grid cell size strongly influenced the results of damage evaluations. The exaggerated estimate realised with the 2D model scenario based on 10m grid cell resolution reveals the limits of using this kind of models with simplified structure for large-scale damage studies. Once the river channel sections are thinner than 10m, large-scale 2D models considering regular grid cells were unable to represent the river flow in the main channel, even for frequent floods (*cf.* the upper bound risk curve in Figure 5).

The sources of uncertainty analysed here propagate differently from one model to another. When comparing these uncertainties in relation to the approaches used (1D, hybrid 1D/2D and full-2D), we notice that the tests realised generated large uncertainties in estimations based on 2D approaches (Figure 7). For both, full 2D and hybrid 1D/2D models the best estimates are placed in the lower limits of the uncertainty boundaries. The best 1D estimate is in the centre of the uncertainty boundary, near the average value.

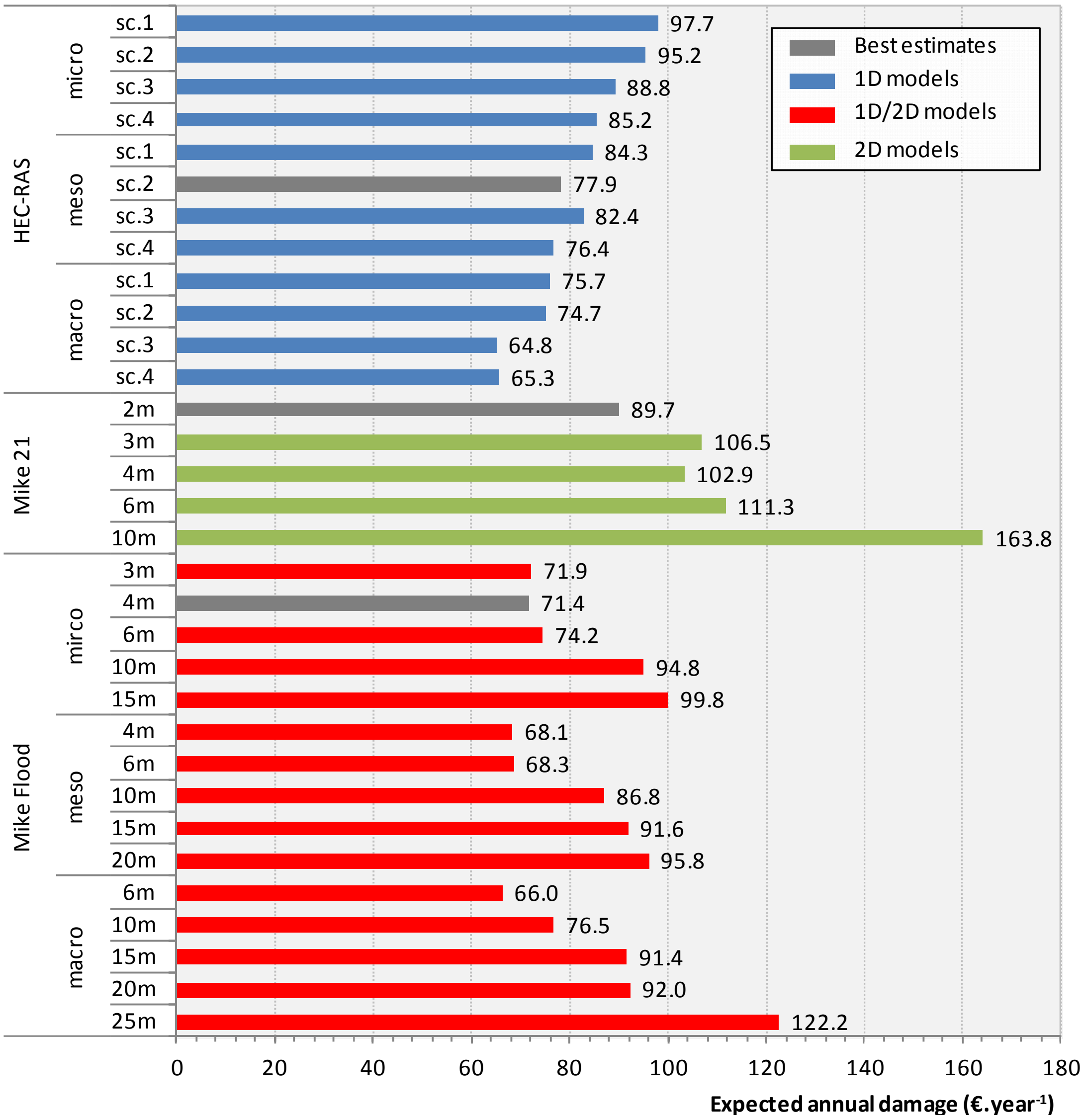

Figure 6: EAD calculated using the different hydraulic modelling strategies.

The model selection uncertainty contributed to 18% of the global uncertainty of EAD estimates generated by the different flood modelling considerations. The parametric uncertainties had a much higher influence on these estimations: they contributed to 75% of the global uncertainty. This strong influence was due to scale considerations, and mainly due to those induced by grid-cell size considerations. On the 1D model (Hec-RAS), the uncertainty relative to the position of cross-sections contributed to only 10% of the 1D EAD estimates uncertainty. The uncertainty linked to scale considerations (density of cross-sections and hydraulic structures) contributed to 95% of EAD uncertainty. By increasing of the number of modelled cross-sections (from macro to micro scale), we induced the increase of predicted flood surfaces and flood damage. This influence was similarly identified for flood areas prediction in the tests realised by Cook and Merwade (2009).

The scale effects on the Hybrid 1D/2D models generated divergent uncertainties on the 1D and 2D parts of the models. On the one hand, the increase of details (from macro to micro scale) on the 1D-part of the models generated an increase of predicted inundated surfaces and damage estimates. The increase of details (from macro to micro scale) on the 2D-part of the models, on the other hand, decreased the surfaces and damage estimates. However, the uncertainty on the 1D-part of the model contributed to 19% of EAD estimate uncertainty against 64% of contribution from the 2D-part related uncertainty. For full-2D models, the scale effect is similar to the 2D-part of Hybrid models. Therefore, contrary to 1D models, the greater the scale of evaluation is, higher the EAD estimation results are.

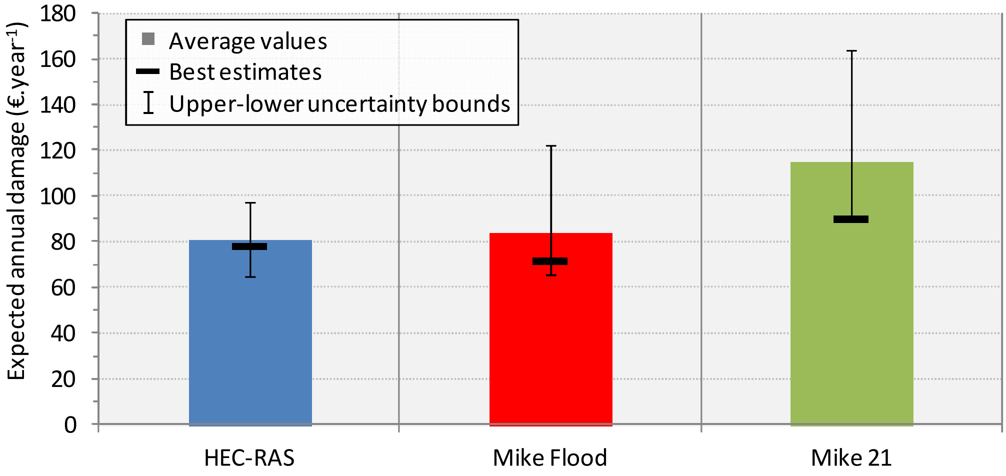

Figure 7: EAD estimated using the different modelling scenarios.

4. CONCLUSIONS

The present analysis highlights that the different strategies used in modelling processes, *i.e.* type of hydraulic model and choices made by the modeller to represent geometry, topography and bathymetry, are determinant for flood maps and damage estimates accuracy. The propagation of uncertainty on damage estimates allowed us to explore some important aspects of the evaluation. We highlight that:

- uncertainty on estimations generated by the flood hazard modelling scale considerations revealed to be much higher than the uncertainty linked to the selection of model. Scale considerations contributed to 75% of expected annual damage (EAD) estimates against 18% for model selection;

- the increasing of the precision of hydraulic modelling has a different impact on damage estimations, according the type of hydraulic approach used. For 1D models, the more detailed the models are (higher density of cross-sections), the higher damage estimation results are. For 2D models, the more the models are precise (small grid-cells) the lower damage estimates are.

- the effect of scale-considerations on 2D-based damage estimates (variability of grid-cell size) is much higher than the effect of scale considerations on 1D-based damage estimates (density of simulated cross-sections);

- damage estimations based on hybrid models are much more influenced by the considerations on the grid-cell sizes than those relative to the number of modelled cross-sections.

The great influence of grid cells sizes revealed by this work is in accordance with literature that considers topography as the main source of uncertainties on flood hazard modelling. On the one hand, topographic reliability depends on the technologies and personal used to acquire the data, and on the methods used to analyze data. Uncertainty could be reduced by adopting the best available technology and by improving performance of the technical staff. On the other hand, this work revealed that it is essential to take necessary precautions when processing topographic data for flood hazard modelling and mapping processes. Hydraulic uncertainty is related to the capacity of the modelling software to represent the flood phenomenon and on the model construction. Several available models, *e.g.* FEMA guidelines list (http://www.fema.gov/plan/prevent/fhm/en_hydra.shtm), are able to correctly represent different types of flood. Though, when accurate data is available, the selection of the appropriate model was less relevant for damage evaluations than the simplifications considered when using them, *i.e.* parametric uncertainty. To reduce uncertainty, the selection of the modelling software has to be in accordance with the characteristics of the site on study, and data availability. Further, the scale of the analysis should not compromise the performance of the selected software. The conclusions of this work are based on a case study and it only considers part of uncertainties related to flood mapping processes. Research is still to be done in order to clarify the global role of hydraulic uncertainty on flood damage evaluations and explore the different criteria that should be considered when realising flood maps for this specific purpose. However, this work highlight that special attention is to be given when using existing flood maps or producing simplified hydraulic analyses for damage estimation purposes. These considerations can strongly affect the results of the evaluation.

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