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On urban inundation and damage modelling

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Abstract: Flood risk results from a complicated interplay of natural and anthropic factors. Therefore, risk modelling and assessment may require different modelling tools, related to individual facets of the problem. These may be organized in a chain where each model represents a ring. The interfaces among the single modelling rings represent a most critical part of the analysis that must be added to the inherent criticalities and uncertainties of each modelling step. In this work a prototypal case-study in northern Italy (the town of Sondrio, that is prone to flood risk by the Mallero river) is considered. A 100-year synthetic river flood was simulated and an outflow hydrograph was accordingly computed in an earlier study. The present work considered the further rings of the chain. A two-dimensional wave flooding the town was numerically modelled, simulating building blocks as impermeable obstructions. Different configurations of the blocks were considered within a sensitivity analysis of the modelling result to the geometric description. Hazard indicators were obtained and transferred to the following modelling ring. Flood-induced damages to buildings, considered proxies for the flood risk, were computed by a recently developed synthetic model, that provides absolute damage values based on a component-by-component analysis of physical damages to residential buildings. In the described sequential procedure, the hydraulic analysis served as a support for the following risk assessment. Therefore, the results of the sensitivity analysis for the hydraulic model were not useful per se but rather with reference to their implications for the quantification of damage and thus of risk.

Key words: Urban flood, risk assessment, two-dimensional wave, damage model

1. INTRODUCTION

Assessment of environmental risks requires consideration of both hazard and vulnerability factors, the former and the latter being mostly related with natural processes and anthropic items, respectively. One way to handle the job is to organize several modelling modules into a chain. For example, Apel et al. (2006) developed a “complete flood disaster chain from the triggering event down to its various consequences”. In such a sequential approach, feedback effects are typically discarded to maintain the modelling chain as simple as possible. Furthermore, different degrees of complexity can be used for the single modelling modules. In all cases, however, key aspects of the study are the identification of the parameters needed in each modelling ring and the capability of the previous rings to furnish their values to the following ones.

This work documents an application of hydraulic risk modelling to a mountainous town situated in Northern Italy. The complete chain was actually split into two parts, with the first one (related with hydro-geologic processes, flash flood in the river and embankment overtopping) developed in an earlier study (Radice et al., 2016) and the following part (related with urban flood propagation and consequent damage to property) developed in this manuscript. Therefore, here two consecutive modelling rings were considered. Following the idea that transfer of information is a key aspect to be taken into account, the objective and main point of interest of the present study was not in the single modelling modules, but rather in assessing the sensitivity of the second module to the implementation of the first one.

2. PRESENTATION OF THE CASE-STUDY

This manuscript considers the town of Sondrio in Northern Italy as a prototypal case-study for application of urban flood and damage modelling. Sondrio (Figure 1) is a 22,000-people town lying on an alluvial fan at the foot of the Valmalenco Valley (350 km^2 wide) in Northern Italy. The fan was created by the Mallero River, which is the main water course of the Valmalenco, with a length of about 25 km. The river enters Sondrio just downstream of a sharp right-ward bend and crosses the town in its last 2 km before flowing as a tributary into the Adda River, which is the major stream of the Valtellina Valley. Elevation in Valmalenco ranges between 280 and 4,050 m a.s.l.; ground elevations in Sondrio are in the range of 280 to 310 m a.s.l., approximately. The position of Sondrio at the foot of a mountainous catchments leads to the presence of significant ground slopes in the town.

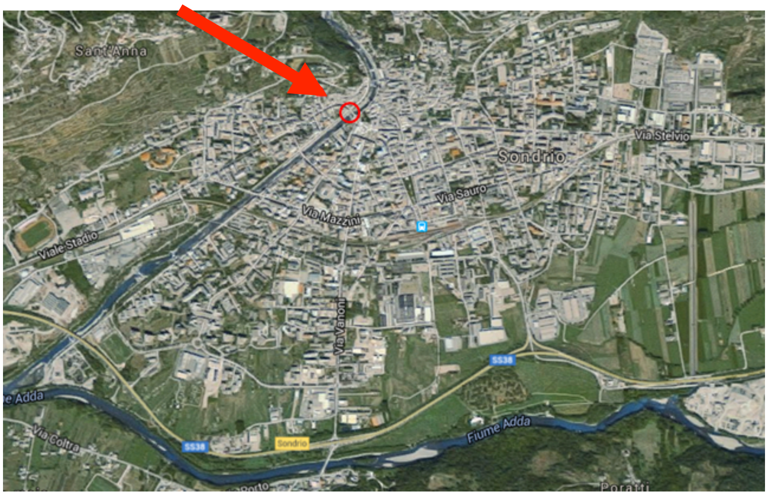

Figure 1. Aerial photograph of Sondrio, with indication of the outflowing location used in the model.

A major flash flood of the Mallero River occurred in 1987. During that event, the town was fortunately not inundated. However, in the following years a major concern of local authorities was stimulated by the event and several studies were performed to assess the flood hazard endangering the town. Thanks to this, different kinds of data are available, making this place a suitable case-study. The authors of the present manuscript have performed in the last years several studies of the hydro-graphic basin morphology (Longoni et al., 2016), river hydro-morphologic processes under different flood scenarios (Radice et al., 2013, 2016; Radice and Elsayed, 2014), flood damages and existing flood management tools (Menoni et al., 2012; Molinari et al., 2013, 2014).

3. HAZARD SCENARIO AND MODELLING CHAIN

A back analysis of the 1987 event showed that, as in other flood events taking place in the twentieth century, the flood hazard for the town was exacerbated by the intense sediment transport in the Mallero River during a flash flood. The transported sediment typically tends to deposit in the in-town reach, due to a much reduced slope of this reach compared to the slopes in the upstream portion of the river. Records of the 1987 flood reported aggradation depths up to 5 m in the in-town reach (for reference, one should consider that the bank height is around 5 to 8 m in the same reach).

The expected phenomenology described above clarifies that any assessment of the flood hazard for the town of Sondrio would require analysis of all the hydro-geologic processes taking place in the hydro-graphic basin, which eventually determine the river hydraulics in the in-town reach that is situated in the final portion of the river. Risk modelling can be organized into a chain comprehending at least (i) hydrologic models for the flood hydro-graph, (ii) models for sediment production in the catchments, (iii) hydro-morphologic models for the river flow and sediment transport, (iv) hydraulic models for the outflowing discharge hydro-graph and (v) for the propagation of a flood wave into the town and (vi) models for expected damages, considered as proxies for the hydraulic risk.

This manuscript considers rings (v) and (vi) of the chain above. The town is flooded with a water hydro-graph that was determined by Radice et al. (2016) as a result of a 100-year flood in the river, corresponding to a 60-hours flash flood peaking at 650 m^3/s. A location where outflow from the river into the town would be most likely was determined (circled in Figure 1), and a flooding hydro-graph was estimated as having a duration of 25 hours and a peak discharge of 140 m^3/s. This hydro-graph is used here as a condition for the following modelling rings.

4. TOOLS AND RESULTS FOR FLOOD AND DAMAGE MODELLING

The urban flood was modelled using the depth-averaged model implemented in River2D (Steffler and Blackburn, 2002). The flood-induced damages were estimated using the INSYDE model by Dottori et al. (2016). This section briefly describes the modelling procedures and the quantitative outputs.

4.1 Urban flood

River2D implements a finite-element solver of the shallow-water equations. In this model, the ground geometry is discretized using an unstructured mesh with triangular elements. Bed resistance is modelled using a Chezy equation while lateral stresses are modelled by an eddy-viscosity approach. The fixed-bed model considers both surface and groundwater flow. Boundary conditions are expressed in terms of a water hydro-graph at an inflow location and a water elevation at an outflow location. These inflow and outflow locations must be defined as portions of the boundary of the computational domain. Consistently with this brief description, the parameters to be chosen by the user are the mesh size, equivalent roughness height, eddy viscosity, transmissivity (T) and storativity (S) of the ground, inflow and outflow locations and boundary conditions. The result of the computation is in terms of spatial maps of several hydraulic properties (water elevation and depth, velocity, and others), or temporal evolution of these properties at some monitoring points.

In the absence of guidelines for the application to a urban flood, the performance of the model was first verified with reference to a laboratory experiment of Soarez-Frazão and Zech (2008), where an idealized city made of 5 × 5 square-based obstacles was impacted by a dam-break wave. Each obstacle was 0.3 × 0.3 m and streets were 0.1 m wide. This experiment is a unique benchmark for two-dimensional models, that was used as a reference also by Petaccia et al. (2010) and Xia et al. (2011). A negative water depth must be used as a downstream boundary condition to mimic the propagation of the wave over an initially dry bed. Buildings can be simulated by impermeable obstructions. For this experimental case, best results were obtained with a model parameterization limiting the groundwater flow ($T = 0.1$ m^2/s, $S = 0.001$).

Also for the propagation of the two-dimensional wave flooding the town, groundwater flow was prevented by suitable parameterization of soil transmissivity and storativity (that were the same as for the idealized town above). Incorporating single buildings into the geometric description would have been unfeasible, therefore building blocks were considered and, similarly to the idealized town, they were simulated by impermeable obstructions. Two different configurations of the blocks were considered within a sensitivity analysis of the modeling result to the geometry used in the numerical simulations (Figure 2). In a first situation (geometry 1 henceforth), the street width was increased to somehow compensate the use of completely impermeable blocks, whilst in a second realization (geometry 2) the obstruction opposed to the flow was more pronounced. With geometry 1 the two-dimensional solver was able to capture the town flooding and the water recession, whereas for geometry 2 solver crash was not avoidable and the recession phase could not be satisfactorily modelled. Spatial distributions of instantaneous and maximum water depth and velocity were obtained, in the first case together with distributions of water residence time. The modelling approach was more sophisticated than that used by Apel et al. (2006) who determined the contour of the flooded area by a purely topographical method (by comparing characteristic water depth with the ground elevation) and than that used by ISMES (1988) and ISMES and CAE (1988) who, for the same case-study considered in this work, modelled streets as a network of one-dimensional channels.

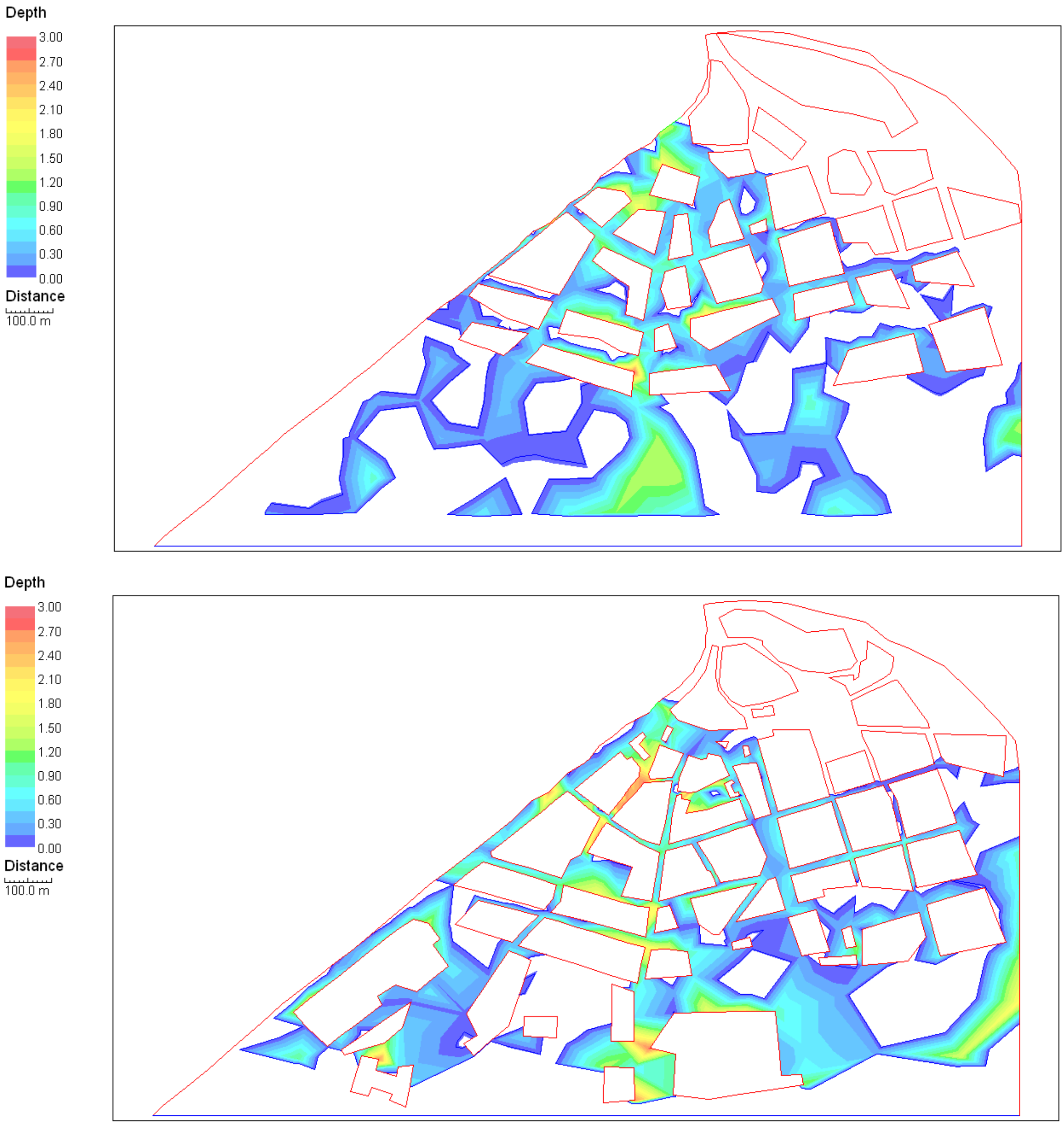

Figure 2. Results for the two-dimensional wave propagation into the town: water depth at peak of inundation for geometry 1 (top) and geometry 2 (bottom).

4.2 Damages

Flood-induced damages to buildings, considered proxies for the flood risk in the investigated scenario, were computed by a recently developed synthetic model, INSYDE (Dottori et al., 2016). This model, that is for the time being suitable to residential areas, provides absolute damage values based on a component-by-component analysis of physical damage to buildings, including costs for removal and replacement of damaged items and plants, structural reconstruction, cleanup and finishing. Absolute damages can be converted into relative ones dividing the model output by the expected cost for building replacement with an analogous one. The model was validated with reference to data for 300 buildings hit by a 2010 flood in Veneto Region, Italy. Parameters to be input to the model include hazard factors (water depth and velocity at peak, duration of inundation, and sediment concentration and water quality as additional parameters) and vulnerability factors (including, among others, the type of building, plan area, number of levels, presence of basement, year of construction, level of maintenance, and building value per m^2).

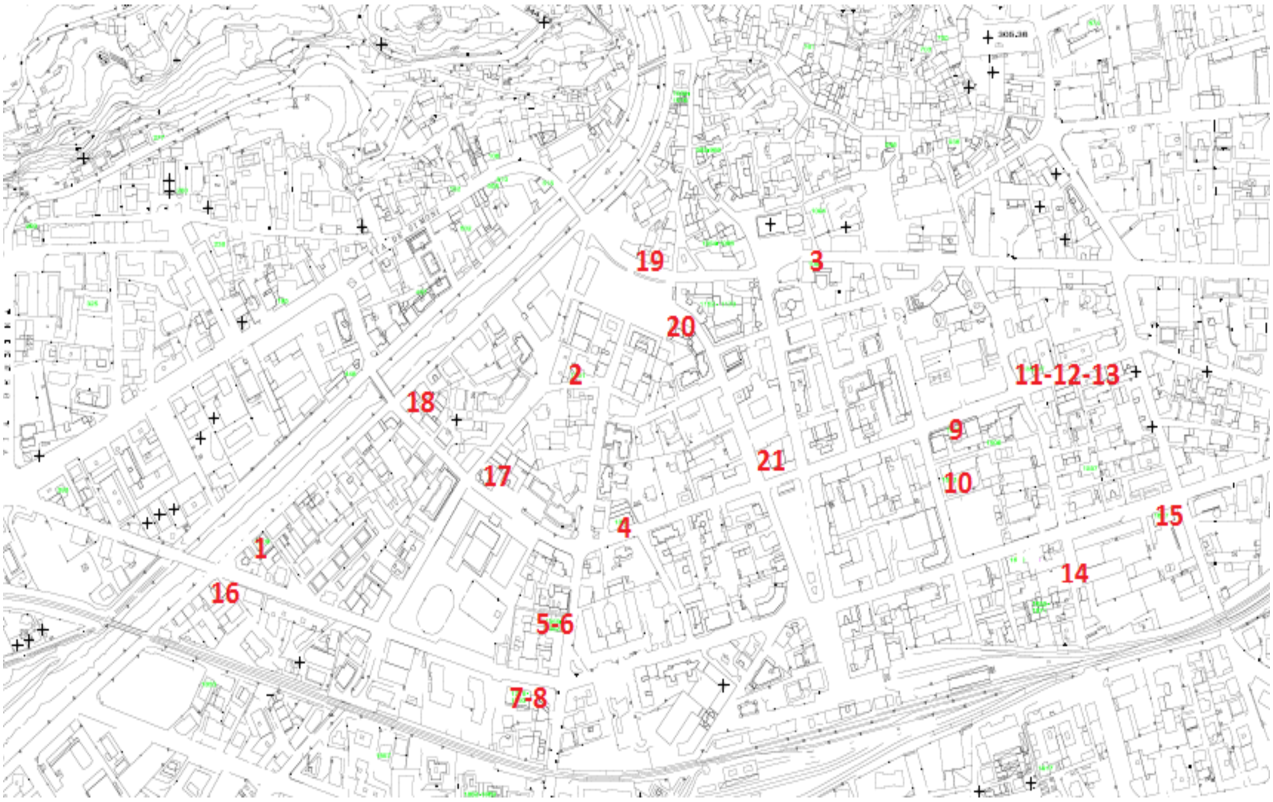

Figure 3. Location of sample buildings.

The properties of 21 sample buildings (Figure 3) were surveyed in the spring of 2016 to determine the minimum set of vulnerability parameters to be input to the model. Hydraulic parameters (water depth and velocity at the peak of inundation, duration for which an item was flooded) were derived from the hydraulic models as those for closest location to the building, or by spatial interpolation. Obviously these parameters could be obtained if they were provided by the model (for example, it was mentioned above that only for geometry 1 the model could be run until the end of the inundation providing the duration of the flood for each building). In case a parameter value was not available, the default value assumed in the INSYDE model was used. Results of the damage assessment are depicted in Figure 4 by a histogram plot of the relative damage. Different damage estimations were obtained for geometry 1 when using only the water depth, or the water depth and velocity, or all the three hydraulic parameters. A major effect sensitivity was detected to the use of duration. Moreover, changing the geometry description to version 2, the damage for some buildings switched from zero (flood not arriving there) to some value, demonstrating the major effect of the geometric description.

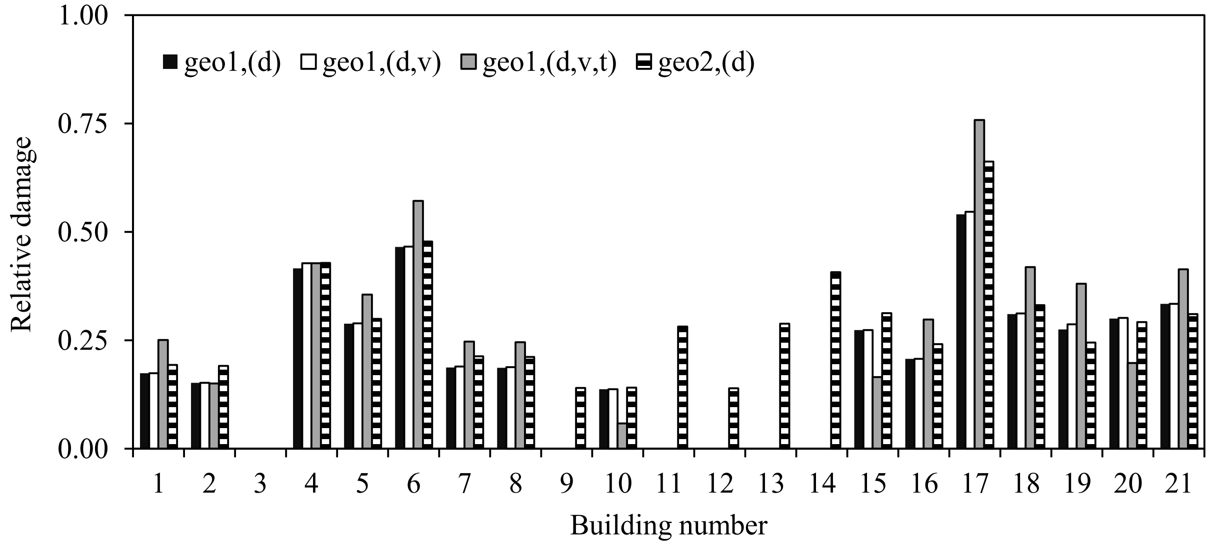

Figure 4. Sensitivity analysis of damage modelling to hydraulic parameters (geometry 1 or 2, using: d = *depth;* d,v = *depth and velocity;* d,v,t = *depth, velocity and flood duration).*

5. CONCLUDING DISCUSSION

In the described sequential procedure, the hydraulic analysis serves as a support for a final risk assessment in terms of expected damage to buildings. Therefore, the result of a sensitivity analysis for the hydraulic model is not discussed *per se* but rather with reference to its implications for the quantification of damage. For example, the damage model used in the present work considers the water residence time as a major factor impacting the absolute damage. Following this, a key feature of a hydraulic model would be represented by its capability to provide a value for such a parameter, and this target should be privileged when running the hazard evaluation. Second, it was found that changing the geometric description of the building blocks could change the water paths up to a level where a building that is completely safe with a certain description can be significantly damaged with another description.

The use of sensitivity analysis was the only possibility to characterize robustness of the results in the absence of appropriate validation data, since fortunately Sondrio was never flooded in recent times. Guidelines for the hydraulic model application were derived from a validation for a laboratory experiment, thus with a huge change of scale.

A major limitation of the present work is related with the prevention of groundwater flow by model parameterization. On the one hand, this sounds reasonable in consideration of the mostly impermeable urban context. On the other hand, it should be borne in mind that in a urban flood the surface flow largely interacts with the sewage system. In principle, even in the absence of a coupled solver for flow over the surface and in the sewer, some coupling could have been obtained also by a different setting of ground transmissivity and storativity. This was not done in the present work because, in the above-mentioned absence of real data, it would have been a mere tentative.

The geometric model used in this work was quite coarse and many specific aspects (e.g. Bazin et al., 2016) were also overlooked. However, the minimum resolution to be used in these kinds of models is an open debate (e.g. Apel et al., 2009; Dottori et al., 2013). On another hand, a high detail would be requested by analyses of the expected damage at the micro-scale (that is considering individual buildings). Combination of an affordable hydraulic modelling with a detailed damage assessment calls for spatial interpolation of hazard indicators, an operation that is not straightforward and can introduce mistakes. Interpolation would also be needed at a further step of the modelling, to convert the damage values obtained for single scattered buildings into a meso-scale damage assessment. This is also a still open issue that shall be addressed by future research.

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