Quantification of flood risk mitigation benefits: a building-scale damage assessment through the RASOR platform

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Abstract

Flood risk mitigation usually requires a significant investment of public resources and cost-effectiveness should be ensured. The assessment of the benefits of hydraulic works requires the quantification of (i) flood risk in absence of measures, (ii) risk in presence of mitigation works, (iii) investments to achieve acceptable residual risk. In this work a building-scale is adopted to estimate direct tangible flood losses to several building classes (e.g. residential, industrial, commercial, etc.) and respective contents, exploiting various sources of public open data in a GIS environment. The impact simulations for assigned flood hazard scenarios are computed through the RASOR platform which allows for an extensive characterization of the properties and their vulnerability through libraries of stage-damage curves. Recovery and replacement costs are estimated based on insurance data, market values and socio-economic proxies. The methodology is applied to the case study of Florence (Italy) where a system of retention

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basins upstream of the city is under construction to reduce flood risk. Current flood risk in the study area ($70\,\mathrm{km}^2$) is about 170 Mio euros per year without accounting for people, infrastructures, cultural heritage and vehicles at risk. The monetary investment in the retention basins is paid off in about 5 years. However, the results show that although hydraulic works are cost-effective, a significant residual risk has to be managed and the achievement of the desired level of acceptable risk would require about 1 billion euros of investments.

Keywords: cost-benefit analysis, exposure, recovery cost, retention basin, GIS

1. Introduction

River floods cause relevant damages to property, infrastructures (Arrighi et al., 2017), public goods, economic activities and services especially when affecting urban areas with important exposed values, such as historic cities and productive sites, thus affecting the whole society. Accurate estimation of flood impacts is crucial to quantify the actual risk and evaluate the cost-effectiveness of hydraulic mitigation works (Förster et al., 2005; Gouldby et al., 2008; Shreve and Kelman, 2014), which require significant investments. Flood impacts estimates are also crucial for non-structural mitigation measures, such as emergency management (Molinari et al., 2013). A deep understanding of flood risk and possible mitigation strategies is unavoidable to communicate technical findings to institutions and firmly support political decision making (Murnane et al., 2016) .

The European Flood directive (EU Parliament, 2007) defines flood risk as the combination of flood hazard, exposure (of population and assets) and vulnerability. The assessment of these three components encompasses various spatial scales, from the catchment, where the structural risk mitigation strategies are designed, to the target receptor (e.g. a single-building or infrastructure) (Burzel et al., 2015). A robust flood risk management strategy usually combines hydraulic infrastructure (e.g. dams, retention basins) (Förster et al., 2005; Gouldby et al., 2008; de Moel et al., 2014), whose aim is the hazard reduction, and local prevention/preparedness actions to address the residual risk (e.g. civil protection warnings, self protection etc.) (Silvestro et al., 2016). The reduction of flood hazard due to engineering works causes a left shift of the damage-frequency curve, thus lowering the curve integral, commonly known as Expected Annual Damage (EAD).

The assessment of flood damage usually relies on the application of stage-damage curves linking flood depth with the expected adverse consequences (Scawthorn et al., 2006; Van Ootegem et al., 2015; Aye et al., 2016). Flood consequences in case of tangible damages are expressed in terms of economic costs. Recovery and replacement costs are the cost per unit area to be sustained to reconstruct the previous building (i.e. the maximum possible damage) and the cost per unit area to replace existing contents respectively. Damages are linked to recovery cost through damage curves, thus actual damage is a fraction of the recovery cost if only renovation or repair are needed. Consequently two main pieces of information are needed, flood hazard maps and vulnerability of the target asset. Within the framework of the EU Parliament (2007) directive, hazard maps are produced by the competent River District Authority in charge of elaborating Flood Risk Management Plan (FRMP) and available as open resource (Sterlacchini et al., 2016). Vulnerability in urban areas is often assessed at micro-scale (Arrighi et al., 2013; Apel et al., 2009; Dottori et al., 2016; Prahl et al., 2016), e.g. at single-building level in order to capture the variability of built-up area in terms of building characteristics (e.g. number of storeys, cellar, construction material) and use (e.g. residential, commercial etc.). However, such a detail requires high-resolution geographic data and attributes. Moreover, major uncertainties still remain in replacement/recovery cost assessment (Meyer et al., 2013) which on one hand may rely on insurance data (Penning-Rowsell and Pardoe, 2012; Rojas et al., 2013; Alfieri et al., 2016), on the other on socio-economic proxies (Arrighi et al., 2013; Marin and Modica, 2017).

The Arno river catchment is one of the largest in Italy with an extent of $9116\,\mathrm{km}^2$. During the catastrophic flood of 1966 the whole catchment was affected (Panattoni and Wallis, 1979; Caporali et al., 2005) and the city of Florence, one of the most important art cities in Italy, suffered of incalculable losses to cultural heritage, buildings, infrastructures and economic activities. Nowadays Florence is still threatened by floods, although some protection measures have been undertaken (e.g. dams, adjustments of dikes and bridges). Flood risk, limited to the urban reach of the Arno river, has been estimated approximately equal to 52 million euros per year (Arrighi et al., 2016a). In the last five decades the Arno catchment has been object of several studies, which identified several retention basins (see Table 1) upstream of the city as the most appropriate flood hazard mitigation strategy. Nevertheless, the flood risk reduction is expected to be marginal also for low recurrence interval events, since a significant urban and industrial development took place in flood prone areas after the 1966 flood.

This work aims at evaluating in monetary terms the relative risk reduction of the planned retention basins upstream of the city of Florence and their cost-effectiveness for the whole urban and suburban area around the historic city. Although a life-cycle approach could be more robust for cost assessment of mitigation works, here only construction and maintenance costs are considered. The risk assessment accounts for several exposed objects, namely buildings, household contents, commercial contents and industrial contents, with the highest possible spatial resolution in order to capture the spatial variability of exposed values of the area. The hazard assessment is based on the official flood hazard maps developed for the FRMP (Autorità di Bacino del Fiume Arno, 2016b). Vulnerability is evaluated at the single-building scale combining several sources of open socio-economic data in a GIS environment in order to enrich the attributes of the exposed asset, thus obtaining a more reliable description of the building use. Replacement costs account for market values, census data and insurance data to properly describe urban spatial variability. Damage calculations are carried out within the RASOR platform (Silvestro et al., 2016; Rudari and RASOR TEAM, 2015; Koudogbo et al., 2014). It is widely acknowledged that a flood damage estimation without validation against local historical loss data may sound weak (Ballio et al., 2015). Unfortunately for the presented case study such data are not available. However, the damage curves libraries of the RASOR platform performed very well in another italian case study when compared to citizen claims and municipal authorities surveys, thus the model is considered reliable at least for comparing several scenarios in the study area (Silvestro et al., 2016; Trasforini et al., 2015). In order to answer the common stakeholders' question "How much should I invest to achieve the desired residual risk?" a section has been dedicated to the description of analytical methods to estimate the benefits of flood risk mitigation and the investment required to obtain an assigned risk reduction.

This article is organized as follows. Section 2 introduces the study area and the risk mitigation measures that have been considered. The methodology to characterize the exposed assets, the costs estimation and risk-benefit analysis is outlined in section 3. The outcomes of the flood risk assessment are presented in section 4. The article ends with the concluding section, elaborating on the effectiveness of measures and future developments.

2. Case study

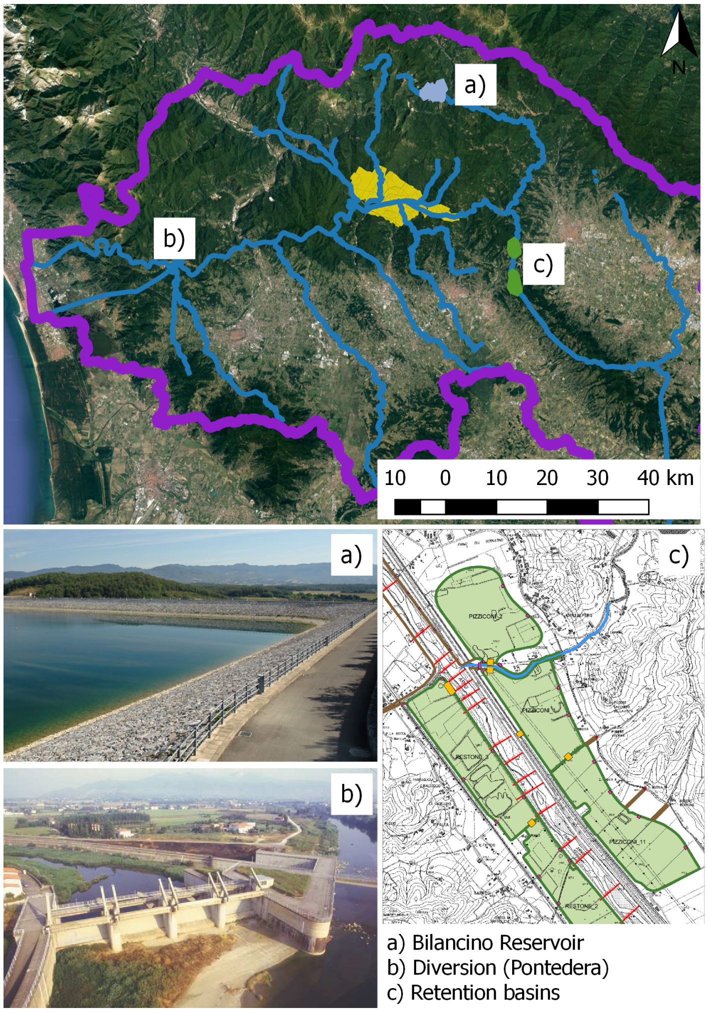

Figure 1: Map of the Arno river catchment showing the location of flood mitigation works: (*a*) Bilancino reservoir (image source www.adbarno.it), (*b*) river diversion (image source www.adbarno.it), (*c*) new system of retention basins (image source Tuscany Region) and the metropolitan area of Florence (yellow area).

The Arno river catchment represented with purple line in the map of Fig. 1, is located in central Italy and covers an area of 9116 km^2 It has 2.2 million inhabitants mostly concentrated along the main stream and its tributaries.

Most of the floodplains along Arno river are protected by dikes. Currently, two main hydraulic works contribute to mitigate flood hazard in the catchment: the Bilancino reservoir and the river diversion in Pontedera (Pisa) Fig. 1.

The Bilancino reservoir (panel a, Fig. 1), operational since 1995, is located upstream of the city of Florence in the river Sieve, one of the main right tributaries of the Arno river. Its maximum storage capacity is 84 million m^3 used for energy production, flood lamination, drinking water supply and recreational purposes.

The river diversion in Pontedera (panel b, Fig. 1), concluded in 1987 is located in the lower Arno stream between Florence and Pisa. Its primary purpose is the protection of the city of Pisa from the floods. The river diversion consist of a 28 km channel capable of diverting a maximum discharge of approximately $1000\,\mathrm{m}^3/\mathrm{s}$ from the Arno river in order to reduce the peak flow discharge in the city of Pisa. During one of the most severe floods in 1992 the channel diverted $900\,\mathrm{m}^3/\mathrm{s}$. Since its construction, the diversion effectively contributed to hazard mitigation 14 times.

The new system of retention basins currently under construction (an example in panel c of Fig. 1) is located upstream of Florence in the river reach between the municipalities of Figline Valdarno and Rignano sull'arno. The projects cost is about 70 million euros and includes four retention basins (Table 1), which are designed to store $22\,\mathrm{Mm}^3$. The alteration of mitigation works over time has not been accounted for. Mitigation effectiveness may vary according to operational protocols of the hydraulic works, currently under optimization.

Table 1: Characteristics of the system of retention basins upstream of Florence. (Designed recurrence interval for activation: 30 years.)

Retention basin	Area (km^2)	Stored volume (Mm^3)	Cost (Mio Euro)
Restone	1.09	6.03	15.9
Pizziconi	1.21	2.47	8.0
Leccio	1.37	6.6	25.0
Prulli	1.34	6.7	25.24

A further measure, currently under study is the increase of the storage capacity of the Levane dam, located upstream of the system of retention basins, with an estimated cost of 25 million euros.

These engineering works have been designed to maximize the stored volume in order to reduce the flood peak discharge in the Florence reach of the Arno river, but so far a quantitative assessment in terms of risk reduction has not been undertaken. The purpose of this study is to quantify the risk reduction and residual risk after the construction of the system of retention basins. The area under study is the city of Florence and its downstream suburban areas which comprise 10 municipalities. In a previous study the direct flood damages of an event of magnitude similar to the 1966 one for the sole urban area have been estimated approximately equal to 4 billion euros (Arrighi et al., 2016a). Of this total amount, 2 billion euros were the estimated losses to buildings, 1.28 billion euros the damages to household contents and the remaining were damages to commercial contents. In that study the census section scale was adopted to estimate flood losses for assigned recurrence scenarios in absence of the new system of retention areas, which at that time were under preliminary design. The census section scale, usually coinciding with a building block in densely populated areas (e.g. historic district) was considered the most suitable scale of analysis for the availability of open socio-economic data and for the possibility of upscaling flood representative parameters (Arrighi et al., 2013). The present study strongly increases the level of detail to the single-building level. Moreover, the census section scale cannot be adopted to the new extension of the study area (117 km^2) since the suburban industrial districts (scarcely inhabited) are discretized with large census sections of the order of 0.3 to 5 km^2 of area which do not provide an adequate resolution of the information to assign the actual flood depth value to each exposed building.

3. Materials and method

3.1. Scales of analysis for hazard assessment

In order to assess the risk reduction due to the planned system of retention basins upstream of the city of Florence the outputs of several scales of analysis are needed (Fig. 2). The hydrologic and climatic characterization of the watershed (left block of Fig. 2) are undertaken at catchment scale in order to produce design rainfall and associated statistical flood scenarios (Campo et al., 2006).

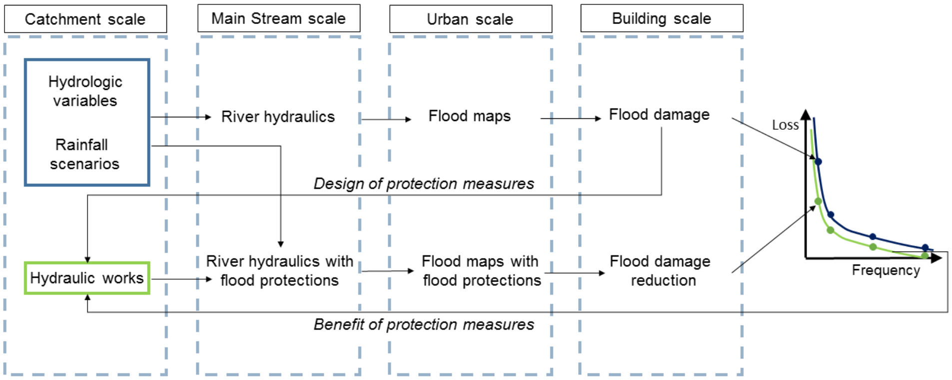

Figure 2: Graphical scheme of the spatial scales involved in flood risk assessment and benefit analysis of hydraulic works.

River hydraulics is performed through a standard solver of the 1D general equation of unsteady flow to obtain water profile along the river. The 1D river model (second block of Fig. 2) uses as boundary conditions the inflow design hydrographs obtained by the catchment scale analysis and quantifies the position and discharge of outflow areas from which the inundation starts. For the considered metropolitan area (third block of Fig. 2) where the outflow from the river banks is present, the inundation volumes are transformed into water depths modeling the floodplain as a system of connected storage areas governed by mass conservation law, stage storage relationships and weir laws accounting for backwater effects for the connection. Being the hydraulic model parsimonious, some phenomena, which may aggravate hazard scenarios such as large wood obstructions or vehicles mobilization have not been considered and are left to a future research. (Ruiz-Villanueva et al., 2017; Arrighi et al., 2016b). For further details on the hydraulic model see the method described in Arrighi et al. (2013), which is adopted by the Arno River Catchment Authority for hazard mapping.

With flood depth maps for each assigned recurrence interval scenario in the urban area (Autorità di Bacino del Fiume Arno, 2016a), including the scenarios with operational system of retention basins, the phases of exposure and vulnerability characterization at the single building scale follow and allows for the assessment of the benefits of risk mitigation measures.

3.2. Exposure characterization at building scale and recovery cost estimation

The exposure analysis aims at identifying at building scale the vertical distribution of the unit use and its representative replacement/recovery value. Here exposure is intended as the ensemble of distinctive parameters which allows for properly assigning damage curves and recovery/replacement cost. If adopting a municipal scale it can be stated that a certain number of buildings are exposed to inundation. With an exposure analysis at building scale it is possible to state for those exposed buildings (whose flood depth is extracted by high resolution hazard maps), the number of floors, the surface area, the building use, the presence of cellar etc. This step is crucial to make then the association with damage curves (sect. 3.3) and recovery costs. The buildings characterization is obtained merging in the GIS environment several sources of open geographic data, available from institutional data portals. The shapefile of the buildings is available at the cartographic scale 1:2000 in the Region Tuscany digital cartography portal (http://www502.regione.toscana.it /geoscopio/cartoteca.html). It provides crucial pieces of information: the number of storeys, the surface area and the main use of the building (e.g. industrial, residential, commercial etc.). However, dual use buildings, where a commercial activity is placed at the ground floor and the residences are located in the upper floors, are the most common in the study area, particularly in the historic district. Dual use buildings are not captured by the 1:2000 building cartography, thus another geographic feature is exploited to refine the exposure classification. The municipalities (http://opendata.comune.fi.it/) distribute a list of commercial activities and their coordinates as point shapefile as shown in panel *a* of Fig. 3, where the green dots localize the direct retail activities.

The application of a three meters buffer to the buildings shapefile allows for the count of commercial activities falling inside the polygon through the $Point - in - Polygon$ vector tool. The size of the buffer has been selected in order to avoid overlaps in the historic district with high buildings density. Residential buildings (according to the regional data source) intercepting commercial activities are classified as dual use buildings, i.e. commercial/residential. Figure 3 compares the original building use in a portion of the historic Florence district with the new building use obtained by the GIS operations. Panel *a* shows the building use as retrieved by the cartography portal, i.e. before the characterization, where the original buildings are represented as residential (light blue polygons). Panel *b* shows the building use obtained by merging the two sources of geographic information, dual use buildings are depicted with a salmon pink color. Thus 14 exposed categories are classified for the risk analysis instead of the original 13. They are residential, commercial, commercial/residential, hospital, school, industrial, place of worship, offices, sport, parking, transport, agriculture, theaters and leisure activities, campings and temporary lodging.

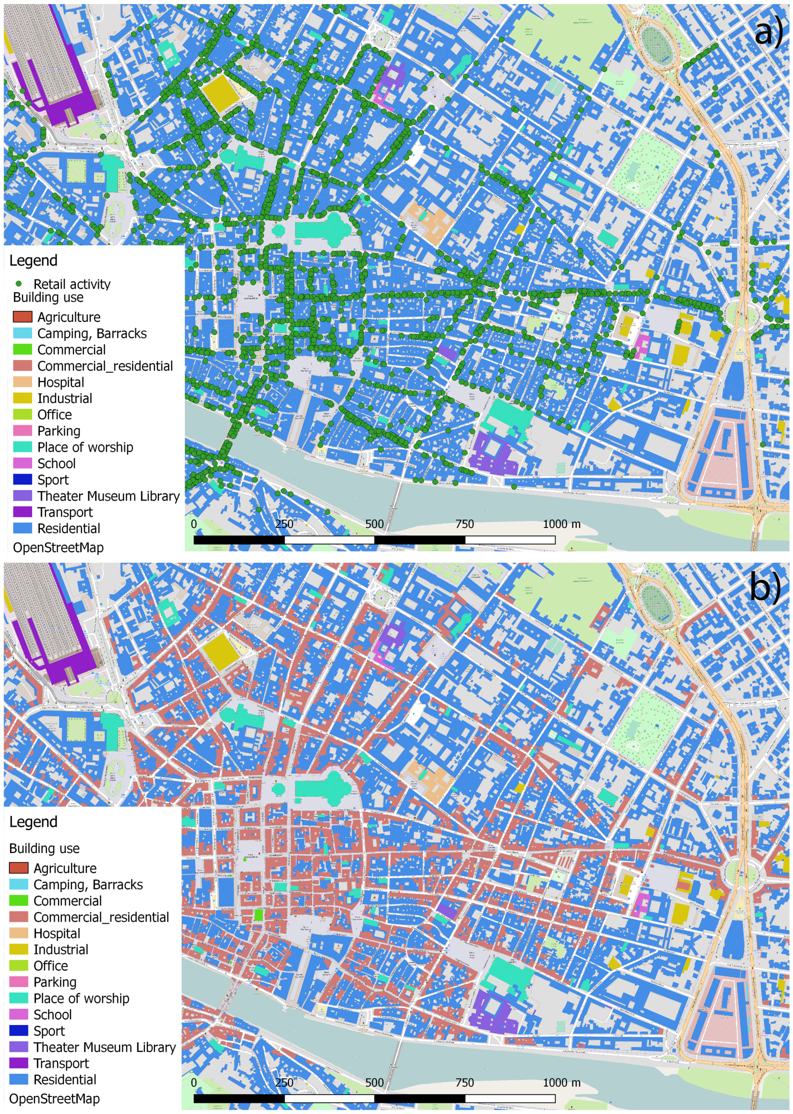

Figure 3: Characterization of single-building use merging the point information about retail activities and main building use (panel a) and the resulting dual use classification commercial-residential (panel b).

Proxies of economic values can be used to estimate the replacement and recovery costs(Arrighi et al., 2013; Marin and Modica, 2017) for structures and contents. The sensitivity analysis carried out in a previous work (Arrighi et al., 2016a) has shown that exposure values, from which the recovery/replacement costs were assessed, is the most sensitive parameter (elasticity=0.9). This bears that if recovery cost changes of 1% the total risk changes of 0.9%. Such a sensitivity is intrinsic of most of damage models since an estimated value (exposure/replacement cost) is multiplied by a relative loss given by damage curves. In this context, where none of the estimates can be validated with historical data, the authors based their the working assumptions on the official insurance data and on the opinion of experts and public stakeholders (co-authors of the manuscript)

In this application, starting from insurance data made available at regional scale by ANIA (Associazione Nazionale fra le Imprese Assicuratrici, 2011) a series of corrective parameters and working assumptions have been defined to adjust regional average values to spatial exposure differences inside the study area. Corrective parameters and economic proxies have been analyzed and assumed based on expert judgment and cooperative debate with stakeholders. The lack of validation data for damage models can be overcome by using the expert's opinion and adopting a what-if approach to synthetically exemplify damage mechanisms and estimate recovery/replacement costs. Where more reliable local data are available, users and practitioners are encouraged to use them for flood risk estimates. As an example of experts' approach, in the historical districts, where there are high finishing levels and strict legislative construction requirements for buildings, the highest recovery cost in the range has been adopted ANIA is a consortium of insurance companies in Italy, which collected citizen claims after several natural disaster, e.g. earthquakes and floods, in the last decades and estimated potential flood losses aggregated by region and building type. For the recovery costs of industrial structures, the corrective parameters P are evaluated using as proxies the market values made available by GIS portal (GEOPOI) of the National Agency for Fiscal Administration (Agenzia delle Entrate, 2017), which collects and distributes sub-municipal scale data about selling and renting values for several categories. A more extensive use of market values has been applied to discern local changes in replacement costs for contents of economic activities, e.g. manufacturing and commerce. Table 2 summarizes the recovery cost of structures used for the damage estimation. The first column indicates the damage category, the second states the source and value of the base cost, the third states the corrective parameter where defined, the fourth the recovery cost adopted in the study, then last column describes how P is estimated. If P is equal to one the base value is adopted.

Most of the recovery costs for damage categories for structures in Table 2 are based on the report about seismic and flood losses (Associazione Nazionale fra le Imprese Assicuratrici, 2011), which collects the average values for each Italian region. Damage categories such as schools, offices, commercial etc. are assimilated to residential building since in the study area these activities are normally hosted in existing buildings and not designed for their current use. Thus their characteristics are strongly similar to residential structures. Hospitals and agricultural buildings recovery values are assessed based on expert judgment. In the first case hospital structures and their constructive details are recognized as being strictly prescribed by law, thus requiring higher recovery costs. Agricultural buildings are usually of poor quality if not used as residences, consequently their value is much lower. Parkings and temporary lodging corrective parameters are estimated using the regional prices for public works (Regione Toscana, 2016). Places of worship have usually a low finishing level, with the exception of those included in the cultural heritage of the historic district, which have been previously studied (Arrighi et al., 2016a).

The replacements costs for contents are summarized in Table 3.

Replacement costs for household contents have been assigned starting from the base recovery value (Associazione Nazionale fra le Imprese Assicuratrici, 2011) for structures and the contents to structure ratio (CSVR) for residential use (USACE, 2006). Several other studies also suggest that residential content is roughly half of the value of the building structure (Huizinga and Szewczyk, 2017). Lower values and high values in the range are assigned to suburban areas and historic district respectively. For commercial and mixed residential commercial contents the base value is the average residential value, which is

Table 2: Recovery costs for structures

Building use	Base value $Euro/m^2$	P	Recovery cost $Euro/m^2$	Description
Residential	1055-1630 (ANIA,2011)	1	1055-1630	Regional value taken as is with maximum assigned to historic districts and minimum to suburbs
Commercial-residential	1055-1630 (ANIA,2011)	1	1055-1630	Regional value taken as is
Commercial	1055-1630 (ANIA,2011)	1	1055-1630	Assimilated to residential buildings
Industrial	1055-1630 (ANIA,2011)	0.8	844-1304	Ratio between residential and productive market values (GEOPOI,2017)
Sport	1055 (ANIA,2011)	1	1055	Minimum of the recovery cost range for structures
Hospital	1055-1630 (ANIA,2011)	1.2	1266-1956	Based on expert judgement
School	1055-1630 (ANIA,2011)	1	1055-1630	Assimilated to residential buildings
Place of worship	1055-1630 (ANIA,2011)	1	1055	Assimilated to low-quality residential buildings
Offices	1055-1630 (ANIA,2011)	1	1055-1630	Assimilated to residential buildings
Transport	1055-1630 (ANIA,2011)	1	1055-1630	Assimilated to residential buildings
Agriculture	1055 (ANIA,2011)	0.3	352	Based on expert judgement
Recreational	1055-1630 (ANIA,2011)	1	1055	Minimum of the recovery cost range for structures
Parking	1055 (ANIA,2011)	0.2	211	Based on regional prices for road infrastructure maintenance (Regione Toscana, 2016)
Temporary lodging	1055 (ANIA,2011)	0.3	316	Based on regional prices for temporary wooden lodging (Regione Toscana, 2016)

Table 3: Replacement costs for contents

Building use	Base value $Euro/m^2$	P	Recovery cost $Euro/m^2$	Description
Residential	1055-1630 (ANIA,2011)	0.5	528-815	Contents to structure ratio (USACE, 2006)
Commercial-residential	671 (Average residential content)	1 1.45 2	671 low dens. 972 medium 1342 high	Based on employees density (ISTAT, 2012) and renting ratio comm/resid. (GEOPOI, 2017)
Commercial	671 (Average residential content)	1 1.45 2	671 low dens. 972 medium 1342 high	Based on employees density (ISTAT, 2012) and renting ratio comm/resid. (GEOPOI, 2017)
Industrial	671 (Average residential content)	1.28 1.54	860 low dens. 1032 high	Based on employees density (ISTAT, 2012) and ratio between industrial and residential renting values in suburban districts (GEOPOI,2017)
Sport	521 (min. resid.)	0.29	150	Based on regional prices for sports infrastructure furniture (Regione Toscana, 2016)
Hospital	521 (min. resid.)	1.15	600	Based on expert judgement
School	521 (min. resid.)	0.29	150	Based on expert judgement
Place of worship	521 (min. resid.)	0.19	100	Based on expert judgement
Offices	1055-1630 (ANIA,2011)	0.3	317-489	Based on expert judgement
Transport	521 (min. resid.)	0.29	150	Based on expert judgement
Agriculture	521 (min. resid.)	0.19	100	Based on expert judgement
Recreational	1055-1630 (ANIA,2011)	0.3	317-489	Based on expert judgement
Temporary lodging	521 (min. resid.)	0.10	52	Based on expert judgement

transformed according to two proxy variables, employees density (ISTAT Istituto Nazionale di Statistica, 2012) and ratios between renting values (Agenzia delle Entrate, 2017).

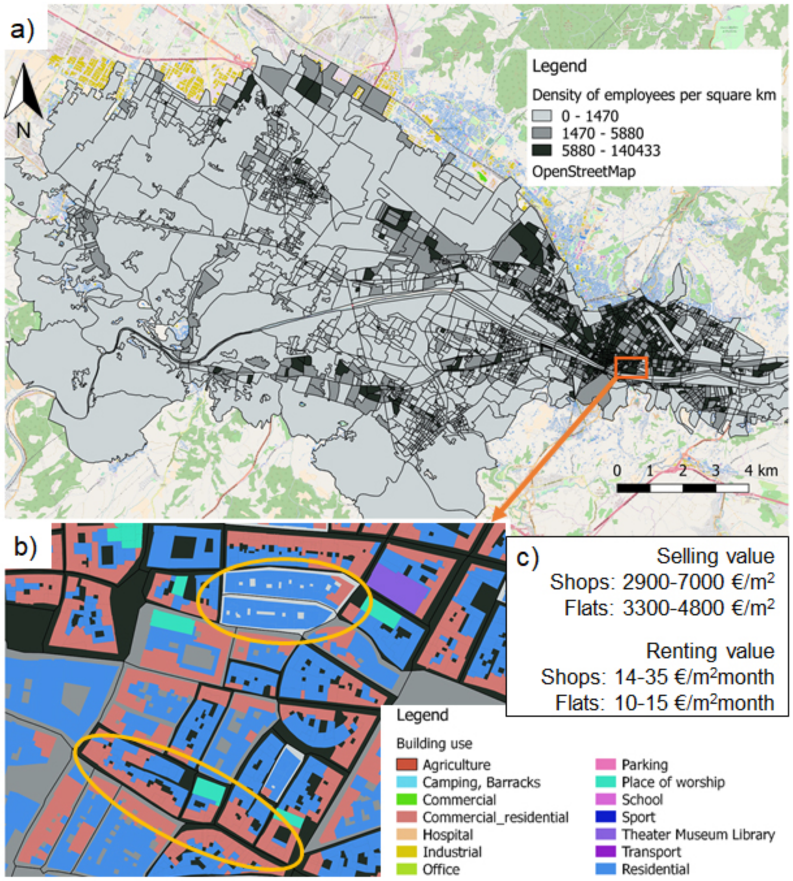

Figure 4: Density of employees per square km (ISTAT, 2012) (panel a), density of employees compared to building use (panel b) and examples of selling and renting values of the area of panel b (panel c).

The employees density shown in Figure 4 for the whole study area (panel a) is considered a reliable socio-economic information which reflects the relevance of economic activities in the census polygons. In panel b of Figure 4 a detail of the historic district of Florence shows that a high density of employees (dark shades) adequately reflects the building use obtained by merging buildings data with direct retail activities list. A comparison can be easily made looking at the top yellow ellipse (panel b of Figure 4) which highlights a building block with one dual use building and low employees density (i.e. light grey background color) and at the bottom ellipse where many dual use buildings are present (i.e. black background color). Renting market values shown in panel c of Figure 4 refer to the same area of panel b. They are affected by the commercial vocation of the area. In fact, renting values of shops are twice the residential renting values. To assign replacement values for commercial and commercial/residential contents the average employees density in the study area is calculated from the census section data (ISTAT Istituto Nazionale di Statistica, 2012). For density lower than the average the parameter P is equal to 1. For density between the average and four times the average P=1.45 and for higher density P=2. These values are calculated as the ratios between the renting values of shops and flats (Agenzia delle Entrate, 2017) in the spatial density clusters. Similarly the replacement costs of industrial contents are assigned using ratios between the renting values of industrial facilities and flats (Agenzia delle Entrate, 2017). The other categories are estimated based on the minimum value for residential contents and on expert judgement because official open data have not been retrieved about these categories. Moreover, the overall impact of these minor classes is quite negligible in the total amount of losses as demonstrated by 7 (panel a), because the sum of residential, commercial, commercial/residential and industrial buildings cover 98.4% of the total number of buildings.

Indirect damages due to the interruption of commercial and industrial activities are evaluated by using as proxy the monthly average national income of the economic sectors multiplied by the number of affected businesses identified by census data (Arrighi et al., 2013; ISTAT Istituto Nazionale di Statistica, 2012). The average length of the business interruption is set equal to two months according to data collected in the last flood events in Tuscany (Albinia (GR), 2014 and Serchio river flood, 2012), where a general alignment has been observed among different economic sectors in the duration of business interruption (Ufficio difesa del Suolo, Regione Toscana, personal communication).

3.3. Damage assessment

Damage computation was carried out through the RASOR (Rapid Analysis and Spatialization Of Risk) platform (Rudari and RASOR TEAM, 2015; Koudogbo et al., 2014), which enables multi-hazard risk analysis for full-cycle disaster management. RASOR integrates diverse data and products across hazards. It allows one to easily update exposure data and to make scenario-based predictions to support both short- and long-term risk-related decisions (Silvestro et al., 2016). RASOR platform allows for the selection of suitable libraries of stage-damage curves, including the HAZUS-MH database (www.fema.gov/hazus) distributed by FEMA (Federal Emergency Management Agency Department of Homeland Security, 2010). The choice of the HAZUS-MH library as the primary set of flood vulnerability functions in the RASOR platform was due mainly to the possibility of assigning curves to a quite general set of building usage classes. This is not the first attempt to use curves defined for the USA context in the European one. For instance, (Jongman et al., 2012) insert the HAZUS functions for a review of flood depth-damage models at land use level in two European case studies, justifying their choice on the basis that they were developed in economically similar regions as the case studies. Moreover, this choice is supported by findings about the comparison of regional-level curves for North America and Europe in a recent JRC technical report (Huizinga et al., 2017); the authors show that the shapes of the functions for residential, commercial and industrial buildings in the two regions is quite similar, the functions for North America being based entirely on the HAZUS flood damage model. Nevertheless, the HAZUS occupancy classification doesnt take into account that European urban centres are rarely characterized by pure-commercial or pure-industrial buildings (this situation being almost non existing in the historical Italian urban centres), these two occupancy classes being usually mixed with the residential one. The original HAZUS-based taxonomy has been thus integrated, and generic mixed-type curves for two given occupancy classes have been developed by merging the corresponding damage curves for the single occupancy classes, the latter being used as bricks to be piled up (Fig. A supplementary material). This approach has been already described in Silvestro et al. (2016). The damage curves included in the RASOR libraries have been validated for the italian case study of Genoa. The 2014 Bisagno flood has been reproduced from the hydrologic and hydraulic point of view and damages have been estimated within the RASOR platform and validated using the citizen claims and post-event municipal surveys showing a good agreement between simulated and recorded flood losses (Trasforini et al., 2015). Although damage curves transferability is a debated issues, the urban characteristics of Genoa do not differ substantially from Florence ones and in absence of local data they are considered reliable. Moreover, a preliminary comparison between the previous study at census scale (Arrighi et al., 2016a) and the current one, has shown a pretty good agreement. The methodology adopted by Arrighi et al. (2016a) had also a good performance in estimating the damages of the Veneto flood (northern Italy) when compared with observed losses (Scorzini and Frank, 2015).

3.4. Risk and benefits of the mitigation measures

Flood risk mitigation works like retention basins are usually designed to retain part of the flow discharge for reference flood scenarios. They have a minimum operational recurrence interval, i.e. they do not work below a certain flow discharge/water stage. This occurs for flood scenarios with expected acceptable losses. On the other hand, for catastrophic floods, i.e. far from the design scenarios, their benefit is extremely low or negligible. A robust risk mitigation strategy is capable of mitigating the adverse consequences of floods for a broad range of recurrence intervals. The benefit of the flood mitigation works for a reference scenario B can be defined as

$$B = 1 - \frac{D_m}{D_0} \tag{1}$$

where D_0 is the damage in absence of any risk mitigation strategy and D_m is the damage with mitigation works.

For high-frequency events, i.e. the mean annual flood, damages do not occur also without retention basins which do not activate, thus B is virtually one. For catastrophic floods i.e. those occurring for recurrence intervals much higher than the design ones D_m tends to D_0, thus B is null. Between those extremes B is comprised between 0 and 1. The mathematical form of B can be expressed as a function of the flood frequency (Olsen et al., 2015) f with the advantage of having just one parameter to be calibrated,

$$B = 1 - \exp(-a \cdot f) \tag{2}$$

where a is a parameter to be determined with estimated values of D_m and D_0 derived by flood hazard and flood damage simulations.

For application purposes, where a limited number of flood damage scenarios in presence of mitigation works are estimated, eqs.1 and 2 allows for evaluating the damage-frequency curve in presence of mitigation strategies by using the following relationship

$$D_m = D_0 \cdot (1 - (1 - \exp(-a \cdot f))) \tag{3}$$

which allows for visualizing the shifted EAD curve. Eq.3 can be used to obtain mathematically D_m for those recurrence intervals where flood maps and damage assessments in presence of mitigation works are not available, having previously calibrated the parameter a (eq. 2) with the available (i.e. simulated) frequency-D_0 and frequency-D_m points.

Residual risk R_r is the fraction of flood risk (as a percentage), which persists after the construction of hydraulic works. Usually, when mitigation strategies are conceived by public authorities, a certain level of flood safety is desired, e.g. zero damage for a given reference flood scenario with assigned probability. R_r can be defined as a function of the amount V (Mio euros) invested in flood risk mitigation. It can be expressed by an exponential law

$$R_r = 100 \cdot \exp(-c \cdot V) \tag{4}$$

where 100 is the actual risk corresponding to zero investments and c is a parameter to be determined using flood risk assessment results.

The intersection between R_r curve and the desired residual risk R_{rd} yields, in principle, the required cost of investment. This does not mean that such as cost is economically and environmentally sustainable nor that is cost-effective.

4. Results and discussion

Four flood scenarios in the current catchment configuration and two flood scenarios with active retention basins are considered. Official inundation maps have been provided by the Arno River catchment Authority. Flood depth maps have a spatial resolution of 1 m based on a LiDAR derived DTM of the same resolution.

Table 4 summarizes the damages estimated for the selected flood scenarios aggregating the losses to structures and contents of the different damage classes listed in Tables 2 and 3. For an event of magnitude similar to the historical 1966 flood the estimated losses in the study area are about 15 billion euros only considering buildings, their contents and business interruption. Overall flood losses would further increase if population, infrastructures, vehicles and cultural heritage were considered.

Table 4: Total flood damages for the considered recurrence intervals and in presence of mitigation strategies

Flood scenario	Total damage (Bln euro)	Total direct damage (Bln euro)	Structures (Bln euro)	Contents (Bln euro)
500-year	14.81	12.71	6.01	6.70
200-year	9.57	8.05	3.75	4.30
100-year	4.47	3.78	1.82	1.96
30-year	0.57	0.49	0.27	0.22
200-year (with retention basins)	8.57	7.17	3.34	3.82
30-year (with retention basins)	0.36	0.29	0.17	0.12

The inundated areas for the four flood scenarios ordered by increased frequency are about $58\,\mathrm{km}^2$, $56\,\mathrm{km}^2$, $40\,\mathrm{km}^2$ and $10\,\mathrm{km}^2$ respectively. Corresponding average flood depths are 1.8 m, 0.95 m, 0.57 m and 0.55 m. With the system of retention basins the inundated area decreases of about $2\,\mathrm{km}^2$ and $10\,\mathrm{km}^2$ for 200 and 30 years flood scenarios respectively and flood depth decreases up to 1 m for both 200 years and 30 years scenarios (see supplementary material, Fig. B, C).

For the 200 years recurrence interval with active retention basins flood depths lowers of about 0.5 m in the historic district of the right bank. In the right bank suburban areas benefit of a 0.3 m reduction of the flood depth. In the left bank, a flood depth reduction up to 1 m is achieved in the historic and semi-central districts. For the 30 years recurrence interval the suburban districts, which are the only affected, benefit of a flood depth reduction up to 1 m.

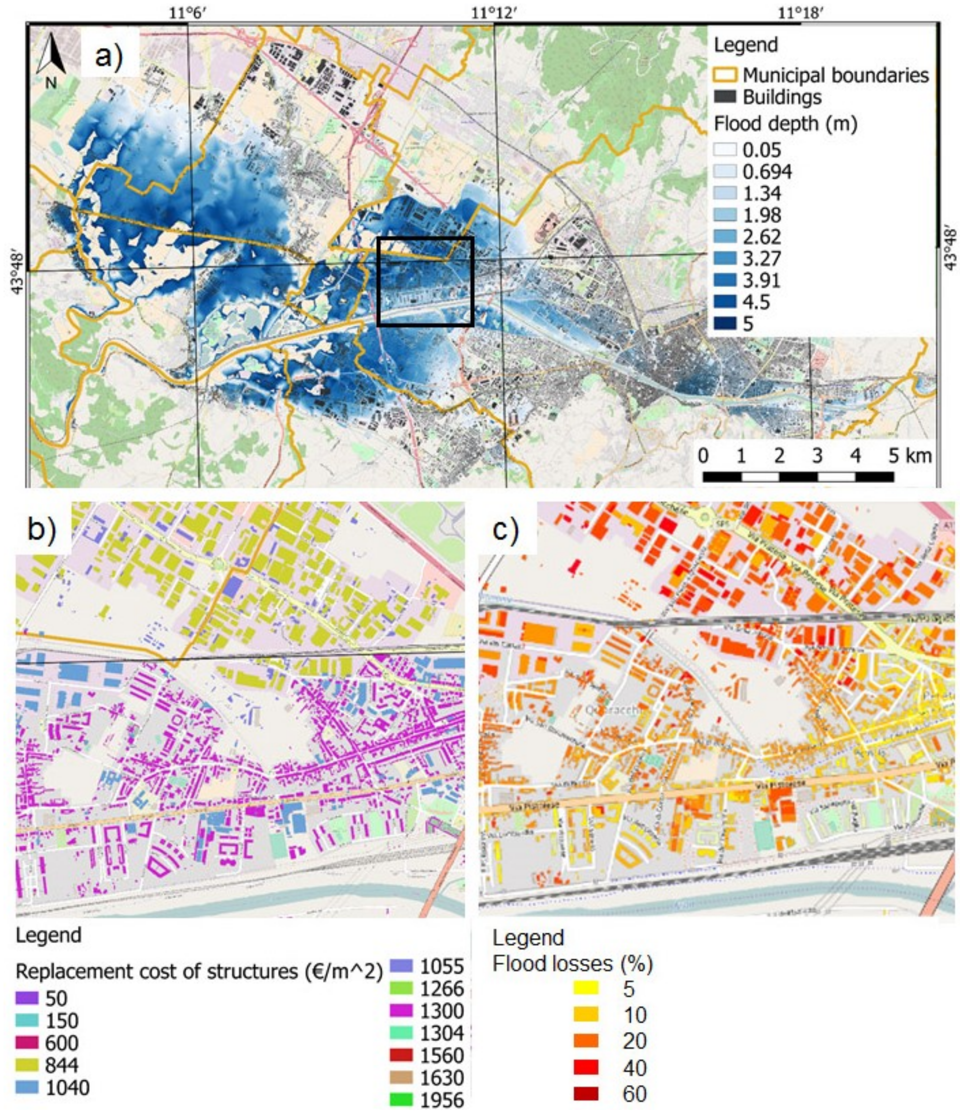

Figure 5: Flood map for the 500-year scenario (panel a), replacement cost for structures (panel b) and relative losses (panel c) in the sub-area indicated by the black rectangle in panel a

Figure 5 shows the flood depth map for the 500 years scenario (panel a) and the building-scale resolution of costs (panel b) and relative damage evaluated through the RASOR platform (panel c). The inundated area is about 58 km^2

and flood depths reach 6 m in the most depressed areas with an average value of 1.8 m. Panel b of Fig.5 shows a detail of the replacement cost for structures in the subset area indicated by the black rectangle in panel a. Residential buildings in this suburban area are assigned the mean value of the range published by Associazione Nazionale fra le Imprese Assicuratrici (2011) (Table 2). Panel c of Fig.5 shows a detail of the relative flood losses in the same area, which range from 5 to 45 %.

Figure 6 depicts the reduction of flood losses operated by the system of retention basins for the 200 years flood scenario. The top and bottom panels show a detail of the relative losses in absence and with risk mitigation works respectively for Signa, which is located downstream of Florence in the south-western part of the inundated area shown in Fig.5. In the Signa area the relative damages decrease from 30% to 5% as shown by the color scale. The use of the building-scale to estimate relative and absolute flood losses allows for properly accounting for the heterogeneity of the urban and suburban conurbation, often characterized by a gradual change in building use and market values moving from historic downtown to industrial areas. Figure 7 shows how the relative distribution of direct flood damages changes in different portions of the study area.

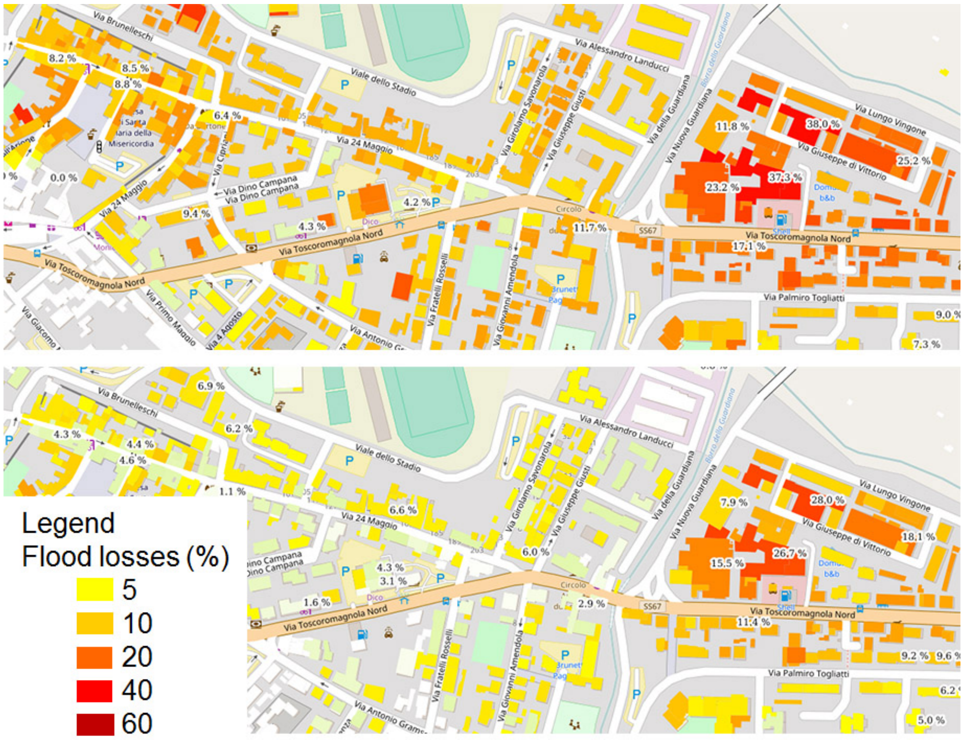

Figure 6: Flood losses in the actual scenario (top panel) and with the system of retention basins (bottom panel) for the 200 years reference scenario in Signa town (south west part of the inundated area in Fig 5).

When the whole conurbation is considered (see Fig.5, panel a) damages to industrial structures cover almost half of the total (Fig. 7, panel a). When only the historic districts are considered (Fig. 7, panel b), losses to commercial activities are dominant over industrial ones and damages to residential buildings represent almost two third of the whole loss.

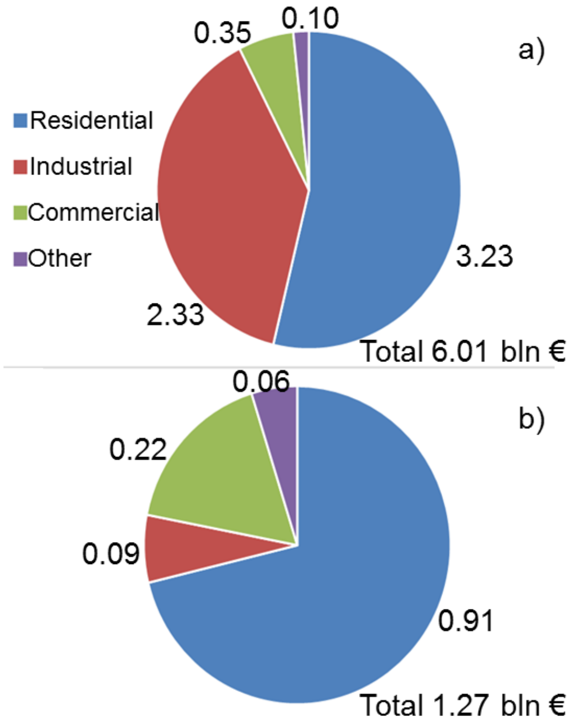

Figure 7: Monetary losses to structures for the 500 years flood scenario. Whole study area including urban area and suburbs (panel a), detail of the urban area (panel b)

The damage-frequency curve is drawn for the total losses (i.e. direct plus indirect due to business interruption) occurring in each base scenario and with the presence of the designed system of retention basins usign eq. 3. Figure 8 depicts in black and red the risk curve for the actual scenario and the scenario with mitigation measures respectively. Apparently the risk reduction due to the system of retention basins is quite low. However, the calculation of flood risk in the two configurations demonstrates that the system of retention basins is cost-effective with the adopted recovery costs and damage curves. Nevertheless, the availability of data to validate the damage model would be relevant to obtain more reliable results, given their high sensitivity with respect to adopted values.

Flood risk evaluated in the current condition is the integral of the black curve of Fig.8 and it is 169.6 Mio euros per year. With the new system of

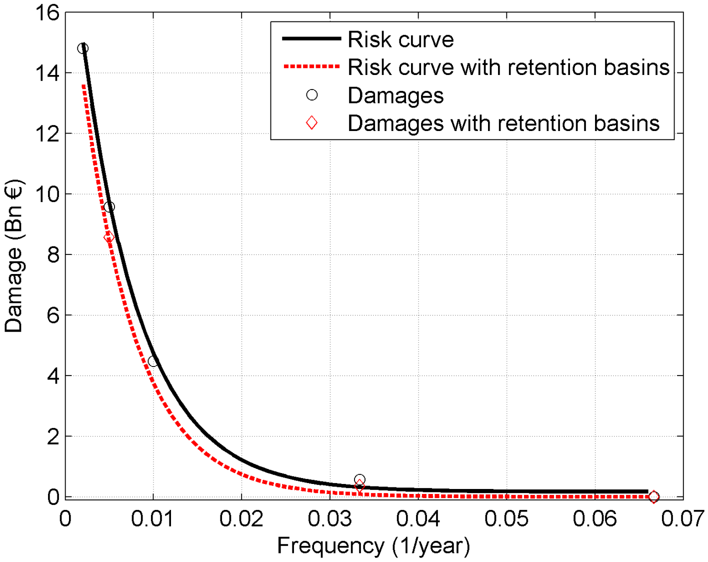

Figure 8: Risk curve in the actual condition and with operational retention basins (the red curve has been slightly shifted to ensure the readability of the plot)

retention basins the (integral of red curve in Fig.8) risk is 151.0 Mio euros per year, with an overall reduction of 18.6 Mio euros per year. This value represents the benefit of the flood risk mitigation measures. Since the estimated cost of the work is 74.14 million euros in approximately four years the initial investment is paid off. Moreover, the annual maintenance costs including hydraulic work supervision and ordinary maintenance of electro-mechanic devices, levees and basins are estimated as being about 2% of the construction cost, i.e. 1.5 Mio euros per year. Thus, they are sustainable with respect to the benefits of the system of retention basins.

In the study area, the authorities would like to obtain zero damages for the 200 years flood scenario through risk mitigation strategies. With reference to Fig.8, this means to shift and stretch to the left side of the diagram the red risk curve in order to set the damage for 0.005 frequency to zero. The desired residual risk R_{rd} is the integral of the new curve and its value, obtained graphically, is about 18% of the current flood risk.

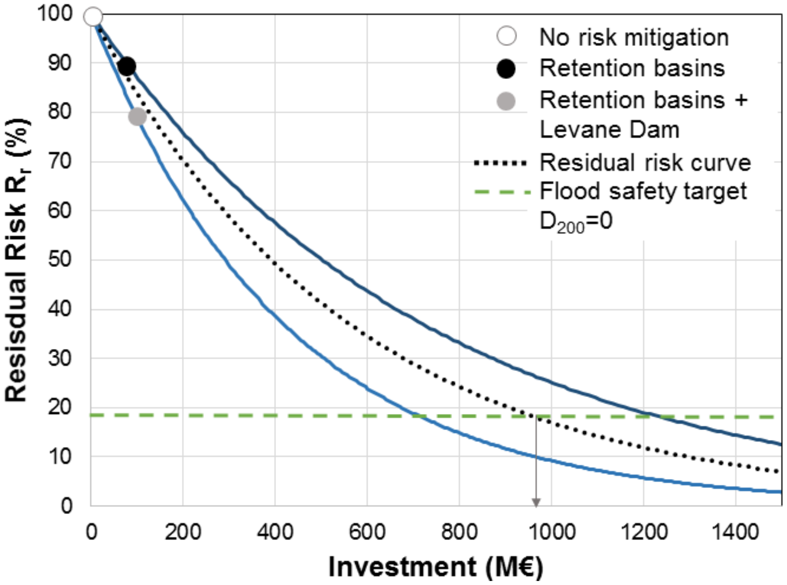

Figure 9: Residual risk curves to obtain the theoretical investment to satisfy the flood safety target (green dashed line)

R_{rd} equal to 18% is depicted in Fig.9 with green dashed line. The upper blue curve represents the regressed exponential curve obtained by eq. 4 using the risk reduction obtained by flood risk estimation carried out accounting for the system of retention basins in Table 1. In this scenario R_r is 89% (black dot). The lower blue curve represents the regressed exponential curve obtained by eq. 4 using the predicted risk reduction achieved by combining the system of retention basins with the increase of storage capacity of Levane dam (grey dot). According to a preliminary hydraulic assessment of the project designers the adjustment of Levane dam crest is expected to have a synergic action with the retention basins, whose benefit is much larger than the sum of the single effects (Regione Toscana, personal communication) with an expected residual risk of 76%.

If both the quantitative risk assessment carried out in this work and the official prediction are used for the regression of the R_r curve (i.e. all the three points are used for calibrating c), the black dotted curve of Fig.9 is obtained. If several risk mitigation scenarios are accounted for and simulated, the shape of the dotted curve better intercepts the theoretical investment required to reach R_r =18% . The intersection with the flood safety target R_{rd} yields a theoretical value of about 1 Bln euros of investments, highlighted by the grey arrow.

4.1. Strengths and Limitations

The work presented in this manuscript has its major strengths in (i) the effort in the characterization of a building scale exposure by merging several sources of open-data, (ii) the capability of handling such a detail in a large case study area by using the RASOR platform, (iii) the presentation of an analytical approach to estimate the investment required for achieved a desired level of residual risk. The research has also some limitations which could be overcome by a future development. Main limitations are first, the use of a parsimonious flood model, which does not account for the cascading effects of possible wood entrainment in the river and vehicles mobilization in the urban area. Second, the damage model is not validated with local data but with a similar urban area in Northern Italy and experts' opinion has been used to overcome the lack of reliable data. Being the recovery/replacement values multiplicative, an error in their estimation propagates in the final damage estimate, with an elasticity equal to 0.9. However, the use of openly available market values to adjust regional average values to local ones is considered as a good compromise to estimate recovery costs in national applications, being aware of the high sensitivity of the final result to these values.

5. Conclusions

This work has described a single building-scale characterization and risk assessment, which is unusual for the large spatial extent of the study area. This was made possible on one hand, thanks to the availability of several sources of open data (buildings polygons and their main use, punctual information on commercial activities) and thanks to the capabilities of the RASOR platform allowing for a simple and robust simulation setup also with cumbersome datasets, on the other. The methodology is easily transferable and adaptable to any urban context where similar urbanization and geographic datasets of exposure (e.g. building polygons) are available. Florence (Italy) is an exemplary case study for the relevance of exposed assets and open data availability. The single building-scale will also allow for tracking the building use changes and recovery cost values in the study area, based on market values updates.

For an event of magnitude similar to the historical 1966 flood the estimated losses in the study area are about 15 billion euros without considering population, infrastructures, vehicles and cultural heritage which would further aggravate the overall impact of the flood event. The cost-effectiveness of the designed system of retention basins upstream of the city of Florence, is considered as demonstrated, although the damage model has not been validated with local data. Nevertheless, a flood risk reduction of 18.6 Mio euros per year, although relevant in monetary terms, is not enough to protect such a large area, especially the suburban areas, which after the devastating 1966 flood has been transformed into a dense productive area ignoring its high flood hazard. Moreover, the flood depth reduction achieved by the retention basins in the historic districts (of the order of 0.5 m) has a marginal effect, thus the management of residual flood risk is fundamental. This may include specific retrofitting measures for buildings and cultural heritage, warning systems and civil protection mechanisms.

The system of retention basins however, is only the first step towards the flood risk mitigation in the Florence area, which remains one of the national priorities. The increase of the storage capacity of the Levane dam (5-7 m of increase of the crest) will also strongly contribute to a further risk reduction and the method adopted in this study could be replicated to evaluate its benefits. The method also allowed for answering a common stakeholders' question, i.e estimating the theoretical investment (about 1 Bln euros) to obtain the desired level of flood safety, i.e. zero damage for 200 years flood scenario. The value appears quite ambitious and does not ensure nor economic or environmental sustainability. However, it demonstrates the need of a more detailed assessment of quantitative risk reduction under further hazard mitigation scenarios and the adequacy of the risk assessment methodology to support stakeholders' decisions.

Software and data availability

The RASOR platform (Rapid Analysis and Spatialisation of Risk) is open access via free registration on the website http://www.rasor-project.eu/. Open data used in the work are available in the following data portals:

- http://www502.regione.toscana.it/geoscopio
- www.adbarno.it/opendata
- opendata.comune.fi.it

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