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Research article

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

Chiara Arrighi [a], [*], Lauro Rossi [b], Eva Trasforini [b], Roberto Rudari [b], Luca Ferraris [b, c], Marcello Brugioni [d], Serena Franceschini [d], Fabio Castelli [a]

[a] Department of Civil and Environmental Engineering, University of Florence, Via di S. Marta 3, 50139 Firenze, Italy
[b] CIMA Research Foundation, University Campus, Italy
[c] Università degli Studi di Genova - DIBRIS, Via Magliotto 2, Savona, Italy
[d] Autorità di Bacino del Fiume Arno, Via dei Servi 15, Firenze, Italy

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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 basins upstream of the city is under construction to reduce flood risk. Current flood risk in the study area ($70\ km^2$) 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.

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

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[*] Corresponding author.
E-mail addresses: chiara.arrighi@dicea.unifi.it (C. Arrighi), lauro.rossi@cimafoundation.org (L. Rossi), eva.trasforini@cimafoundation.org (E. Trasforini), roberto.rudari@cimafoundation.org (R. Rudari), luca.ferraris@cimafoundation.org (L. Ferraris), m.brugioni@adbarno.it (M. Brugioni), s.franceschini@adbarno.it (S. Franceschini), fabio.castelli@unifi.it (F. Castelli).

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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 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.

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

2. Case study

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 m^3/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 m^3/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