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Modelling flood impacts, resilience and risk in art cities

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Abstract: Natural hazards might cause irreversible impacts to cultural heritage that for its unicity has an intangible value. The difficulties in describing exposure and vulnerability of this peculiar asset make risk and resilience assessment rarely applied. This work describes a novel flood resilience modelling framework encompassing inundation modelling, exposure analysis, vulnerability, and recovery dynamics. The method is applied to cultural heritage in Florence (Italy) a UNESCO world heritage site which hosts 10 million visitors per year. Results are obtained in terms of indirect losses per flood scenario, recovery times and risk.

Keywords: vulnerability, exposure, hydraulic modelling, cultural heritage.

1. Introduction

Cultural Heritage plays a fundamental role in post-disaster resilience of communities and art cities (Galloway et al., 2020). One of the definitions of resilience is “the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard” (Heinzlef, eta al., 2020; McClymont et al., 2020). Post-event recovery is facilitated by the revenues generated from tourism activities, although this depends on the magnitude of impact as well as the efficiency of community participation and governance. Quantitative approaches for assessing flood resilience are commonly based on indicators which evaluate system performances; however, conceptual and theoretical frameworks are more popular and highlight difficulties in operationalizing resilience (McClymont et al., 2020).

This work introduces a quantitative resilience model to simulate the post-flood recovery time and associated indirect impacts based on new concepts for exposure and vulnerability (Arrighi et al., 2022). The method is applied to the art city of Florence (Italy).

2. Materials and method

The modelling workflow is summarized in Fig. 1. The workflow starts with a flood model which simulates the flood propagation in the river with a 1D computational scheme and the flood propagation in the urban environment with a 2D scheme. Several probabilistic scenarios which differ for the flow hydrograph set-up as boundary condition are simulated. Probabilistic flood depth maps are obtained to perform the exposure analysis based on the polygon shapefile of cultural buildings.

Exposure value of cultural heritage is hardly monetizable, in fact non-economic values are usually considered to rank or classify cultural significance, such as spiritual, historical, symbolic values etc. Many countries use different regulatory frameworks to protect cultural heritage, thus implicitly recognizing a higher cultural value to UNESCO World Heritage sites (international interest), then to national heritage and local heritage (regional/municipal interest) (Romão and Paupério, 2021). While this framework is adequate for large-scale cultural heritage risk analysis, for a city-scale risk assessments, especially when the study area is an art city listed as UNESCO heritage site, might not be adequate since it does not allow to distinguish non-monetary values among several cultural buildings, which would collapse to the same class of significance (Arrighi, 2021).

In this work exposure intangible values are approximated with the number of visitors to cultural buildings based on crowd-sourced data. In fact, for those attractions without official reports, a site-specific regression model is obtained to estimate the annual number of visitors based on the number of Tripadvisor reviews.

This framework for exposure estimates a proxy for social value of cultural heritage based on visitors' appreciation in a UNESCO art city context where, among many attractions, tourist have to choose what to visit during their stay, thus this is a measure of social preference.

To estimate indirect impacts a depth-idleness vulnerability function is introduced. Against the direct losses to CH which occur because of the physical contact of water and the building/artwork, art cities are often constructing preparedness plans which allow for moving artworks to safe elevations after a flood early warning. Nevertheless, in absence of retrofitting or prevention measures, cultural buildings can be affected and remain idle for the time required to repair/restore the structure. For low water depths, e.g., of the order of few centimeters, a deep cleaning and safety check can be enough to reopen the attraction, while for high water depths above 4-5 m, such as in the 2002 Elbe flood in Dresden, the process may take months.

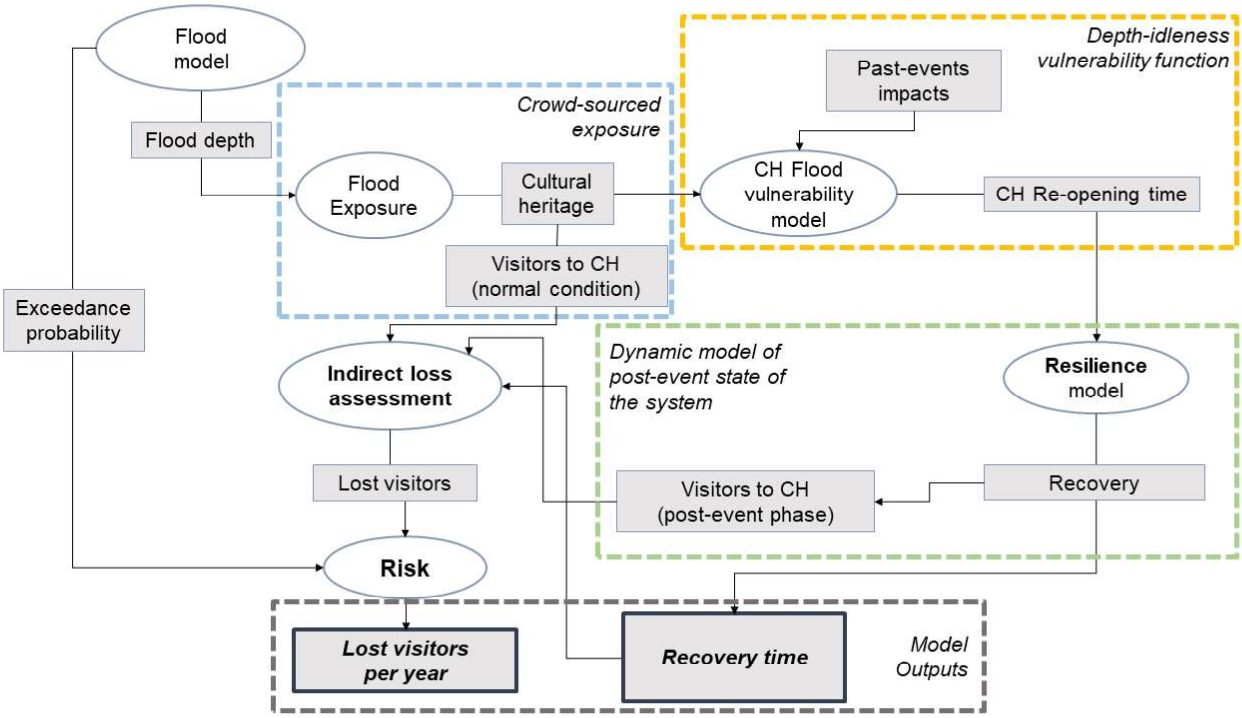

Figure 1 – The resilience modelling workflow. Ellipses are models, boxes represent data flow (adapted from Arrighi et al., 2022).

A review of flood events occurred in art cities and affecting museums and cultural heritage has been carried out to gather information about the water depths, reopening times and event description. This analysis yields the depth-idleness vulnerability function of Eq. 1

$$T_O = 93.46 \cdot h \tag{1}$$

Where h is the average flood depth (m) on the building footprint and T_O is the reopening time (days).

The resilience model describes the temporal dynamics of visitors V(t) after the event (Eq.2) in a system state where attractions and museums reopen at different times depending on the severity, i.e., flood depth of the event (Eq.1).

$$V(t) = V_{pot} \left(\frac{\sum_{i=1}^{m} V_{i,0} \, M_i(t)}{V_{pot}} \right)^k \tag{2}$$

where V_{pot} are the normal visitors when all attractions are open, $V_{i,O}$ are the visitors after the event of the open attractions $M_i(t)$, where $M_i(t)=0$ if $t<T_O$ or $M_i(t)=1$ if $t \geq T_O$, m is the total number of attractions, and k is an exponent that determines the attractivity of the whole art city.

The difference between normal visitors V_{pot} and post-event visitors $V(t)$ is the loss of visitors that occurs after the event and reduces back to pre-event values. The total value of this indirect impact is obtained by integrating the difference V_{pot} - $V(t)$ into the t_{end}-t_{shock} recovery time for each flood probabilistic scenario with assigned return period T_R. Indirect flood risk from visitor loss is given by Eq. 3

$$Risk = \int_0^1 \int_{T_{shock}}^{T_{end}} V_{loss}(T_R, t)\ dt\ d\left(\frac{1}{T_R}\right) \tag{3}$$

3. Results

The application of the resilience model to the city of Florence considers 4 hazard scenarios (T_R=30-, 100-, 200-, 500- years recurrence intervals) simulated with a 1 m resolution LiDAR-based digital terrain model. There are 175 buildings classified as cultural heritage for which exposure analysis is performed. For each of them, data on normal visitors are collected (here updated to 2019), which are for the whole city about 10 million per year. The Uffizi, the Cathedral, and the Galleria dell'Accademia stand out with more than 1 million visitors per year. The attractivity factor k is assumed equal to 3.

For an event with a return time of 30 years, the historical city centre and its cultural assets are not flooded. For less frequent events the estimated recovery times are 36, 351, 393 days for T_R equal to 100, 200, 500 years respectively (Fig. 2). Lost visitors for the 200-year scenario are about 10.5 million. A sharp increase in the number of visitors that correspond to the reopening of the most visited assets allow us to identify a possible strategy to accelerate the post-flood recovery. The increase in site attractiveness is in fact a parameter that allows in the short term to recover more quickly, while in the medium to long term the ability to reopen all attractions is crucial. The application of Eq. 3 results in a risk deriving from the indirect loss of visitors of around 88 thousand per year, equal to around 1% of normal annual visitors.

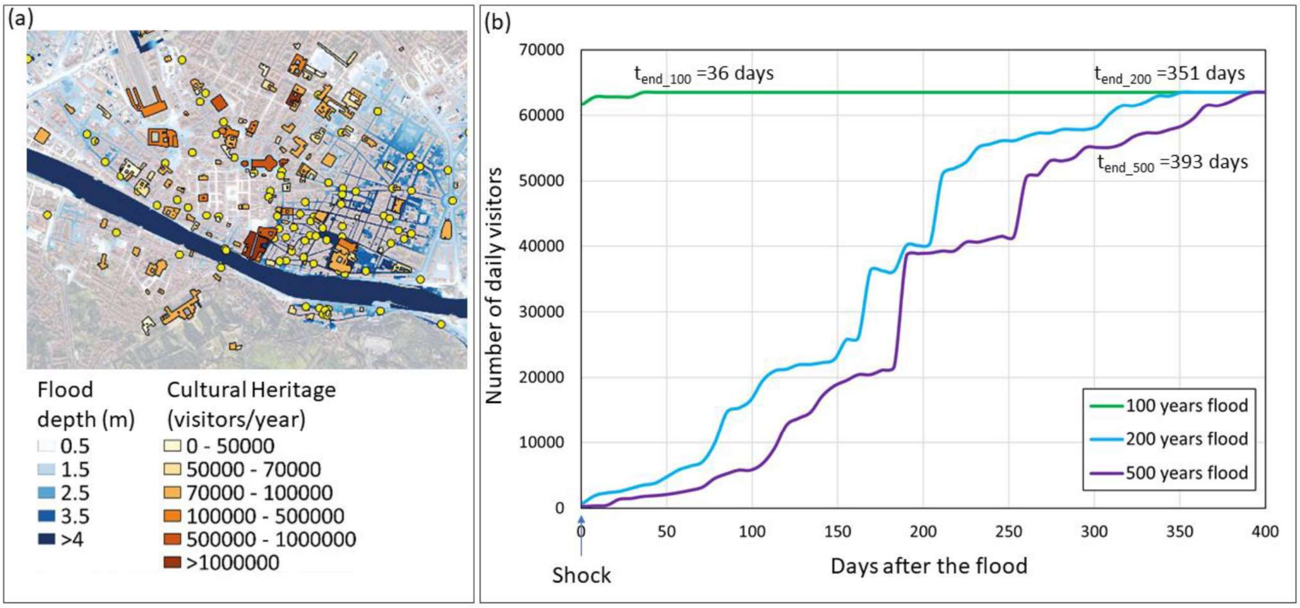

Figure 2 – Flood depths for TR= 500 years, and visitors to cultural heritage in normal conditions (a); resilience of the city after the shock for three flood scenarios (b)

4. Conclusions

The model here introduced makes explicit the strong link between resilience, indirect impacts and flood risk and could be extended to other hazards or contexts using different state variables and vulnerability functions. For the case study the water depth assigned to cultural heritage is evaluated at the terrain level, so the peculiarities of individual buildings that could have raised or lowered ground floors compared to the main road level are neglected. Such structural peculiarities could significantly affect resilience especially for highly visited cultural properties. This aspect will be addressed in future research with building-specific hazard and exposure analysis. Further studies should investigate the effects of prevention and mitigation measures on recovery dynamics and also on flood losses to artworks and cultural buildings.

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