A Mass Appraisal DSS for the Assessment of the Cost-Effectiveness of Flood Mitigation Interventions

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Abstract. This study presents a mass appraisal decision support system (DSS) and computational framework for the assessment of avoided flood damages and the evaluation of flood-risk-mitigation measures at the regional scale. The proposed approach integrates hazard assessment, exposure quantification, and vulnerability analysis to estimate damage to assets and industry in the status quo ("as-is") and post-intervention ("planned") scenarios. Avoided damage estimates are combined with intervention costs to derive a cost-effectiveness index of the investment undertaken, which remains consistent across different types, scales, and locations of interventions, and enables a coherent comparison of alternative solutions within a unified framework. This makes the approach particularly suitable for screening and ranking multiple mitigation options in complex territorial systems. The framework is applied to a levee breach scenario along the Piave River (northern Italy), where two alternative locations of the same intervention are evaluated. Results show a significant reduction in expected damages and clearly highlight the higher effectiveness of one solution compared to the other.

Keywords: Flood hazard modeling · Damage assessment · Cost-effectiveness

1 Introduction

Climate change is generating significant modifications in hydrological and meteorological regimes worldwide and across the European Union, including the amplification of extreme rainfall events, the intensification of storms, and the progressive rise in mean sea level. These drivers are producing, at both national and regional scales, an escalation in the occurrence probability and severity of flood phenomena. Floods are among the most common disasters in Europe [1, 2]. According to the European Environment Agency, over the period spanning 1980 to 2023, flood-related events across EU Member States resulted in the loss of 4,226 lives and generated annual average economic losses estimated at EUR 7.8 billion [1]. Notably, exceptional damage levels were recorded in 2021 and 2023, with total losses rising to about EUR 48.2 billion in 2021 and EUR 25.7 billion in 2023 [2]. Furthermore, national-scale impacts were particularly significant in Italy, where flood events in 2024 produced overall damages worth EUR 10 billion [2]. In

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addition to causing injuries, mental trauma and deaths, floods impact property, infrastructures, and services, which can be destroyed or severely damaged. The unpredictability and magnitude of intense rainfall events represent a primary driver in flood risk management, which necessitates the deployment of reliable monitoring and prediction systems, and the design of resilient hydraulic systems and flexible risk mitigation approaches, aimed at safeguarding communities and critical infrastructure prone to flood hazard. It is expected that, in the next decades, flood risk and related economic loss will increase in Europe [1]. Consequently, enhancing the resilience of territories and implementing effective strategies to reduce hydrogeological risk have become central objectives in Governments' agendas and risk management policies.

Under these evolving boundary conditions, public decision-making assumes a strategic role in ensuring sustainable and technically sound planning. In this respect, Directive 2007/60/EC, better known as the Floods Directive on the assessment and management of flood risks, requires EU countries to: *i)* identify all areas potentially prone to significant flood hazard; *ii)* map the extension of these areas and the assets and population exposed within; *iii)* implement adequate and coordinated measures to reduce flood risk in these areas. Moreover, it is worth mentioning that Directive 2007/60/EC emphasizes the rights of citizens to access the above information and contribute their opinions throughout the planning process.

The intrinsic complexity of public decision processes, characterized by the interaction of multiple stakeholders, heterogeneous interests, and potentially competing objectives, requires the adoption of structured, transparent, and scientifically sound decision-support systems. Populations require, indeed, strengthening the legitimation, accountability, and transparency of public decision-making processes devoted to the design, ranking, and selection of flood risk mitigation interventions [3–5]. The structuring of robust decision-aiding processes and the provision of advanced and sound decision support systems are, consequently, essential to rule out arbitrariness in decision-making and assist planners and policy-makers in evaluating alternative risk mitigation measures and managing flood risk under increased uncertainty on hydrological patterns due to climate change, operational constraints, and an ever-stringent lack of financial resources.

In this paper, we propose a parsimonious decision support system (DSS), namely a simplified, low-variable methodological framework to evaluate the cost-effectiveness of alternative interventions (by type and/or location) to reduce damage in areas prone to flooding. We provide an assessment index based on avoided damage by comparing the status quo ("as-is" scenario) and the scenario after the intervention has been undertaken ("planned" scenario). In detail, our approach integrates hazard, exposure, and vulnerability into a mass appraisal valuation, and computational framework aimed at supporting decision-making at the regional scale. In other words, we couple advanced hydrodynamic modeling to define hazard scenarios with a mass appraisal procedure to assess damage to assets and industry potentially caused by floods in the status quo and post-intervention scenarios, respectively. Formal models permit improving the accountability of decision-making processes and pose the basis for participatory decision-making; by contrast, they can induce a possible loss of global insight and involve a cost for using them. The main objective of our contribution is to provide decision-makers with an assessment model that is robust; nonetheless, it includes a reasonable number of state

variables, and is fed via the largest possible number of open source or easily accessible data. On the one hand, data scarcity represents, *de facto*, a major issue, particularly in areas with limited monitoring of infrastructures. On the other hand, information needs to prove theoretical soundness and operational completeness: information and knowledge need to be exploited consistently and coherently, and need to be meaningful and useful for the final user and/or the purpose they have been designed and constructed for [4, 6].

The remainder of the paper is organized as follows. Section 2 briefly presents the related literature; Sect. 3 introduces materials and methods to clarify the methodological fundamentals of the proposed approach and data used for the modeling; Sect. 4 provides and discusses an illustrative example to prove the potential and the ease of use of the proposed approach; finally, Sect. 5 concludes.

2 Related Literature

In recent years, the increase in the frequency and intensity of flood events has been mainly attributed to climate change, urbanization, and land-use modifications. About 4% of floodplains and 40% of urban areas are covered by surfaces that do not allow water to seep into the ground, and about 12% of the EU's population lives in floodplains [1, 7]. This context challenges policy makers and governments to adopt advanced tools for flood risk assessment and support in decision-making [8–10].

In this respect, it can be observed in the literature an advancement from traditional deterministic models toward integrated approaches combining hydrological and hydraulic models, socio-economic analyses, and artificial intelligence (AI). This evolution has led to the development of multidisciplinary frameworks aimed at improving the design and successful implementation of flood risk mitigation strategies [11]. Traditional flood risk assessment models are based on the physical simulation of runoff and inundation processes, and allow the estimation of water depth, flood extent, and flood propagation time. They have recently included in the modeling open-database for simulating fluvial dynamics and socio-economic impacts to improve the assessment of potential damages and support land-use planning activities [12]. The introduction of probabilistic models in this domain has enabled the consideration of climate uncertainty and the simulation of multiple flood scenarios that, in turn, have improved the robustness of decision-making processes. Specifically, the integration of climate change projections into flood modelling represents one of the main current research directions in this field [13] meant to improving the assessment of extreme event probability of occurrence and enhancing resilience-based planning strategies [14].

According to the existing literature, the development of innovative DSS, which integrate hydraulic models, geographic information systems (GIS), and socio-economic data represents one of the major research interests in flood risk management. Nonetheless, the edge of research on DSS includes the integration of advanced tools (e.g., deep learning algorithms, urban digital twins), and multiple criteria evaluation models. The former contributes to supporting policy makers in infrastructure investment planning and improve allocation of resources [15], and the latter to prioritizing interventions based on infrastructure resilience, social vulnerability, and effectiveness of risk mitigation measures [10, 16]. It is worth mentioning that the recent deployment of AI has positively

impacted flood prediction, mapping of flood-prone areas, and damage assessment via machine learning [11, 17] and deep learning techniques [15, 18, 19], which are also becoming widely adopted to increase transparency and understanding of decision models and improve institutional acceptance, which are fundamentals when modeling is used to support policy-making and strategic planning [19].

A well-established strand of literature focuses on the assessment of economic losses caused by flood events. Starting from the seminal contribution by Merz et al. [20], many reviews have been recently conducted, as reported by Romali et al. [21] and Olesen et al. [22]. Most studies focused primarily on direct damages to buildings and urban areas [23–25]. In addition, recent studies have also reported modeling errors generated by less accurate or improper procedures of data aggregation [26–29] and the lack of high-resolution damage models. Consequently, the development of reliable valuation frameworks to assess economic losses remains a priority research area.

Finally, as it emerges from the literature, regardless the tremendous advancement in research mentioned above, data limitation and availability remain still a critical challenge in this domain, as obviously incomplete datasets may reduce the reliability of model outputs [12, 21, 30].

The aim of this paper is to contribute to filling some of the existing gaps in the literature, primarily identified in the provision of multidisciplinary and integrated valuation approaches and standardized DSS, which can be easily scaled and implemented also in areas where data scarcity is particularly limiting a robust damage assessment.

3 Methods

The valuation approach we propose can be structured into the following sequential steps (Fig. 1).

1) The first step involves the identification of the hazard-impacted area, defined as the spatial extent where the intervention is expected to modify hazard conditions.

For any return period relevant from a hydraulic perspective, we assume that the extension of the area is equal in the "as-is" and "planned" scenarios, with the only difference being the hazard level, which may change due to the intervention. This ensures that the spatial domain under investigation is comparable in the two scenarios. The area must be sufficiently extensive to capture all the relevant effects of the intervention while remaining reasonable in scope. In the case of floods, it basically corresponds to the inundated area in the "as-is" condition.

2) The second step involves the assessment of hazard, exposure, and vulnerability.

Within the impacted area, the hazard indicates the potential to generate damage. It can be expressed either in terms of physical variables (e.g., water depth and flow velocity in the case of floods), or as discrete hazard classes. Hazard is estimated through dedicated analyses carried out during the design phase. In the case of floods, they include two-dimensional (2-D) hydraulic modeling that provides spatial distributions of water depth and velocity. For the "as-is" scenario, they are also available from existing hazard maps (e.g., flood maps provided within the EU Floods Directive), while dedicated analyses are required for the "planned" scenario. This approach allows for areas characterized by certain hazard levels in the "as-is" scenario to be reassigned to lower or zero hazard

in the "planned" scenario. The approach also accounts for residual hazard in case the intervention does not fully eliminate flood hazard for a given return period.

Exposure is defined as the economic value of assets located within the hazard area, including buildings, infrastructures, and population, and it is assessed based on the same underlying hypotheses in the "as-is" and "planned" scenarios. Exposure evaluation first considers the spatial distribution and the number of assets, which are derived from existing cartographic and statistical sources. For example, buildings are characterized based on their location, footprint, and functional category. The economic value of assets is then assigned according to homogeneous categories based on local data. For example, building values are estimated using official property databases, considering the municipality and urban zone, while commercial and industrial activities are evaluated using sector-specific data, such as classifications based on economic activity and average revenue.

Vulnerability quantifies the proportion of the exposed asset that is expected to be damaged under a given hazard intensity. It is a function of hazard characteristics (e.g., water depth and flow velocity), and varies spatially according to hazard distribution. The same framework is applied to both the "as-is" and "planned" conditions, with differences arising only from changes in hazard levels. Specifically, vulnerability is expressed as a value between zero (no damage) and one (total loss), and it is estimated through damage functions relating hazard intensity to expected damage for different asset categories, including buildings and industrial structures. These functions are typically derived from literature or empirical data, even though vulnerability can be conservatively assumed equal to one for the damaged items.

3) The third step includes the assessment of damage in the hazard-impacted area.

Damage depends on hazard, exposure, and vulnerability. For each spatial unit $(x,y)_k$ and asset category i, damage is estimated as:

$$D_{i,(x,y)_k} = E \cdot V(H) \tag{1}$$

where E is the economic value of assets of category i in $(x,y)_k$, and $V(H)$ is the vulnerability associated with the hazard level H. Total damage is obtained by summing across the spatial units and the asset categories:

$$\mathrm{D} = \sum_{\mathrm{i}} \sum_{k} D_{i,(x,y)_k} \tag{2}$$

This calculation is performed separately for both the "as-is" and the "planned" scenarios, namely $\mathrm{D}_{as\text{-}is}$ and $\mathrm{D}_{planned}$.

The benefit B obtained from the intervention is defined as the reduction in damage:

$$B = \mathrm{D}_{as-is} - \mathrm{D}_{planned} \tag{3}$$

4) The fourth step includes the definition of a cost-effectiveness index and its calculation to provide a project ranking from the most to the least cost-effective.

The cost-effectiveness index I_{CE} is defined as the ratio between the avoided damage and the costs of the intervention C:

$$I_{CE} = \frac{\mathrm{D}_{as-is} - \mathrm{D}_{planned}}{\mathrm{C}} = \frac{B}{\mathrm{C}} \tag{4}$$

This index provides an objective measure of the intervention's effectiveness in terms of avoided damage and construction costs.

The general framework can be extended to consider multiple events over the service life T_U of the infrastructure. Each event is associated with an annual exceedance probability p_j (where $j = 1,\ldots,n$), and the probability domain is discretized into intervals Δp_j (i.e., the discretized annual exceedance probability interval associated with p_j). In the "as-is" and "planned" scenarios, the total damages over T_U, denoted as $\overline{\overline{D}}_{\text{as - is}}$ and $\overline{\overline{D}}_{\text{planned}}$, respectively, are given by:

$$\overline{\overline{\mathrm{D}}}_{\text{as - is}} = \overline{D}_{\text{as - is}} \cdot \mathrm{T_U} = \left(\sum_{\mathrm{j}} \mathrm{D}_{\text{as - is,j}} \cdot \Delta \mathrm{p_j} \right) \cdot \mathrm{T_U}$$

$$\overline{\overline{\mathrm{D}}}_{\text{planned}} = \overline{\mathrm{D}}_{\text{planned}} \cdot \mathrm{T_U} = \left(\sum_{\mathrm{j}} \mathrm{D}_{\text{planned,j}} \cdot \Delta \mathrm{p_j} \right) \cdot \mathrm{T_U} \tag{5}$$

where $D_{as\text{-}is,j}$ and $D_{planned,j}$ denote the damage associated with the probability level p_j and $\overline{D}_{as\text{ - }is}$ and $\overline{D}_{planned}$ are the expected annual damages in the "as-is" and "planned" scenarios [31].

The benefit and cost-effectiveness index can be calculated as in Eqs. (3) and (4).

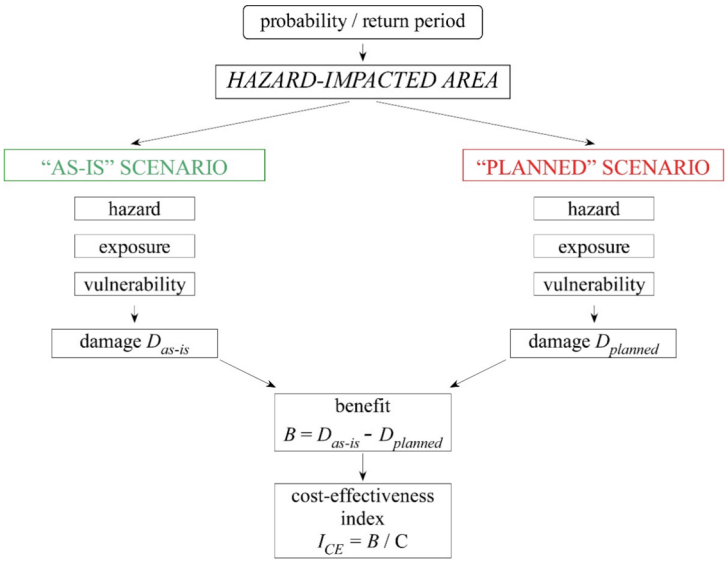

Fig. 1. Conceptual map of the proposed approach (workflow).

4 Application Example

As an application example, we consider a flood scenario induced by levee breaches. We assume a hypothetical intervention designed to prevent levee collapse at two potential breach locations, named B1 and B2. In the "as-is" state, the damage scenario corresponds

to the envelope of maximum water levels from both possible breaches. In the "planned" scenario, the intervention is implemented at one of the two locations, effectively excluding that breach from contributing to damage estimation. For the sake of simplification, we consider only a return period of 30 years (i.e., $p = 1/30 = 0.033$).

This example is meant to illustrate the potential of the valuation framework and the user-friendly procedure implemented for calculating the cost-effectiveness index I_{CE} and for ranking the two potential locations of the same intervention from best to worst in terms of cost-effectiveness. The extension of the framework to diverse and multiple interventions is straightforward and follows the same computational framework.

In addition, for the sake of simplification and according to the objective of the present section mentioned above, we considered only damages to buildings and industry as a proxy for damage. Nonetheless, this approach can be extended to include other types of losses to cover the full range of direct and indirect loss to tangible and intangible assets generated by floods.

4.1 Study Area

The study area is located in the Veneto Region (northeast of Italy), in the municipality of San Donà di Piave, adjacent to the Piave River. The Piave River, 230 km in length, has an average flow of around 100 m3/s and can convey discharges up to ~ 2700 m^3/s during flood events. In the study area, the river spans around 100–200 m in width and is separated from the surrounding floodplains by continuous levees approximately 6 m high. The terrain slopes southeast, with elevations ranging from 5 m above sea level near the northern levees to below 0 m in the southeastern portion.

Elevation data are derived from LiDAR surveys conducted between 2004 and 2009 by the Italian Ministry of the Environment and Energy Security, providing both a digital surface model (DSM) and a digital terrain model (DTM) at a spatial resolution of ~ 1 m. These data are available from the online atlas Geoportale Nazionale (https://gn.mase.gov.it/portale/home, accessed on 29 March 2026).

4.2 Hydrodynamic Model

The flood hazard scenario in the study area is simulated using the 2-D hydrodynamic model '2DEF', which enables a physics-based representation of river flow, levee failures, and the inundation of adjacent areas in a coupled framework. The model solves a modified form of the shallow water equations that incorporates wetting–drying processes [32], and it employs a mixed Eulerian–Lagrangian approach for momentum conservation [33].

The equations the model solve are:

$$\begin{aligned}
&\frac{\partial h}{\partial x} + \frac{1}{g}\frac{\mathrm{d}\left(\frac{q_x}{Y}\right)}{\mathrm{d}t} + \frac{q_x|\mathbf{q}|}{K_s^2 H^{10/3}} - Re_x = 0 \\
&\frac{\partial h}{\partial y} + \frac{1}{g}\frac{\mathrm{d}\left(\frac{q_y}{Y}\right)}{\mathrm{d}t} + \frac{q_y|\mathbf{q}|}{K_s^2 H^{10/3}} - Re_y = 0 \\
&\eta(h)\frac{\partial h}{\partial t} + \nabla\mathbf{q} = 0
\end{aligned} \tag{6}$$

where h represents the water level, g is gravity, t is time, Y is the volume of water per unit area, H indicates an equivalent water depth that is useful for describing partially wetted areas [31], η is the portion of wetted area per unit area, K_S is the Strickler roughness coefficient, $\mathbf{q} = (q_x;q_y)$ is the vertically integrated velocity, and $(Re_x;Re_y)$ are the dimensionless Reynolds stresses in the horizontal plane.

To efficiently represent rural floodplains, the model couples 2-D triangular elements with 1-D channel elements for the minor drainage network, that is not explicitly resolved by the 2-D representation. Special 1-D elements also allow modeling hydraulic structures, pumping stations, and levee breaches caused by overflow or piping.

The 2DEF solver has been successfully applied to simulate both river flows [34–36] and urban flooding [37–40]. In the present case, the model was used to simulate the Piave River from Nervesa della Battaglia to the Adriatic Sea. The computational domain covers approximately 589 km^2, with a flexible unstructured mesh whose elements range from ~ 500 m in rural areas to less than 100 m in urbanized zones. Model calibration and validation were performed against multiple gauging stations along the river in previous studies [41].

For the present analysis, a realistic flood event with a return period of 30 years was considered, based on the local Basin Authority assessment. The event has a total duration of 98 h, with a peak discharge of approximately 3000 m^3/s at $t = 50$ h.

The simulation incorporates hypothetical levee breaches to evaluate potential flooding under both "as-is" and "planned" conditions, providing a consistent framework for assessing the effectiveness of proposed interventions. The breaches were initiated after the flood peak had passed, at $t = 70$ h. To represent the breach, the levee crest elevation was reduced by 90% of its height on the floodplain side over a 30-min period. The breach width was assumed to be 230 m, corresponding approximately to the riverbed width at points B1 and B2. The 2D model, including the surrounding floodplain, then simulates the propagation of the resulting flood wave across the area (Fig. 2).

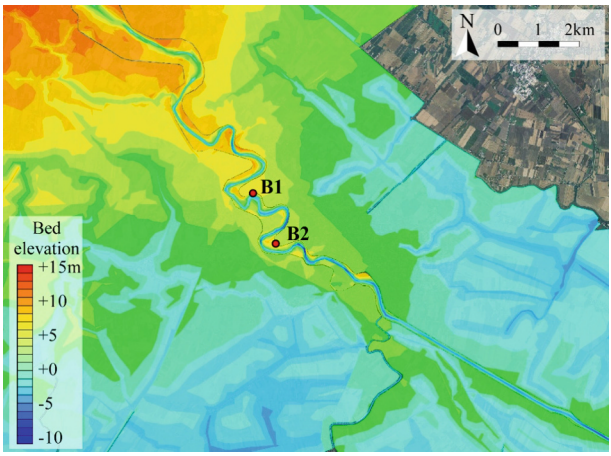

Fig. 2. Study area: bathymetry and identification of levee breach locations

4.3 Hazard Scenarios and Hazard-Impacted Area

Hazard scenarios are constructed based on the hydrodynamic simulations for both the "as-is" and "planned" conditions. In the "as-is" condition, the hazard is defined by the envelope of the maximum flow depths and velocities associated with the two potential breach locations (B1 and B2), as illustrated in Fig. 3a. In the "planned" conditions, two alternative scenarios are considered: P1, in which breach B1 is prevented, and P2, in which breach B2 is prevented, and the hazard scenarios are defined accordingly, as shown in Fig. 3b and Fig. 3c.

The hazard-impacted area is then identified based on the inundated extent obtained from the "as-is" condition, which represents the maximum spatial extent of flooding across the considered scenarios. This area covers a surface of 26.6 km^2 and is delineated by the red line in Fig. 3. It is subsequently used as the reference domain for the analysis.

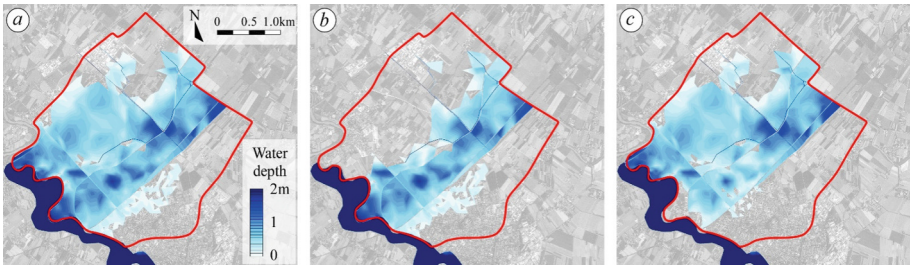

Fig. 3. Water depth predicted by simulations with the 2D hydrodynamic model for the "as-is" (a) and the "planned" scenarios P1, P2 (b,c).

4.4 Assessment of Damage to Buildings

Damage to buildings is assessed by combining information on exposure, hazard, and vulnerability. First, buildings located within the hazard-impacted area are identified and

characterized (Fig. 4a). Building footprints are extracted from the regional technical cartography (CTR), providing information on both the spatial location and the ground floor area of each building. In addition, the total floor area of the buildings is estimated based on the footprint area and the number of floors as described in [36], starting from the Digital Surface Model (DSM) obtained via the Geoportale Nazionale (see Sect. 4.1), and assuming an average inter-floor height of 3.5 m.

Property market data and value are derived from available open-source datasets. In particular, the unit market value (EUR/m^2) for different building typologies and locations, is here derived from the real estate market database provided by the Italian Real Estate Market Observatory (Osservatorio del Mercato Immobiliare, OMI) of the Italian Revenue Agency, and it is assigned to each building in the hazard-impacted area, as illustrated in Fig. 4b. The market value is used as it is more readily available and consistently accessible at the regional scale compared to construction cost data.

The estimation of direct damage is then performed by combining hazard and exposure information through a vulnerability function. For each building polygon, a lumped impact parameter for hazard, named W, is computed based on local hydraulic conditions (water depth Y and flow velocity U), according to the formulation proposed by Lazzarin et al. [42]:

$$\mathrm{W} = \frac{Y}{3.5}\left[1 + 0.3\left(\frac{U}{\sqrt{gY}}\right)^2\right] \tag{7}$$

This parameter is used as input to a damage function that expresses the relative damage as a function of hazard intensity. For the present application, the vulnerability (i.e., the relative damage) is computed following [42], where different vulnerability functions are defined depending on the building typology and number of storeys. For example, for masonry single-storey buildings, which are the most common in the study area, the vulnerability function is:

$$V(W) = \frac{1}{1 + 2.1/W} \tag{8}$$

For each building, the relative damage is first estimated based on the local hydraulic conditions and then converted into absolute economic loss by multiplying it by the total floor area and the assigned unit value. Finally, the damage to residential buildings is obtained by summing the contributions of all buildings within the hazard-impacted area. The spatial distribution of relative damage for the considered event is shown in Fig. 4c-e for the considered scenarios.

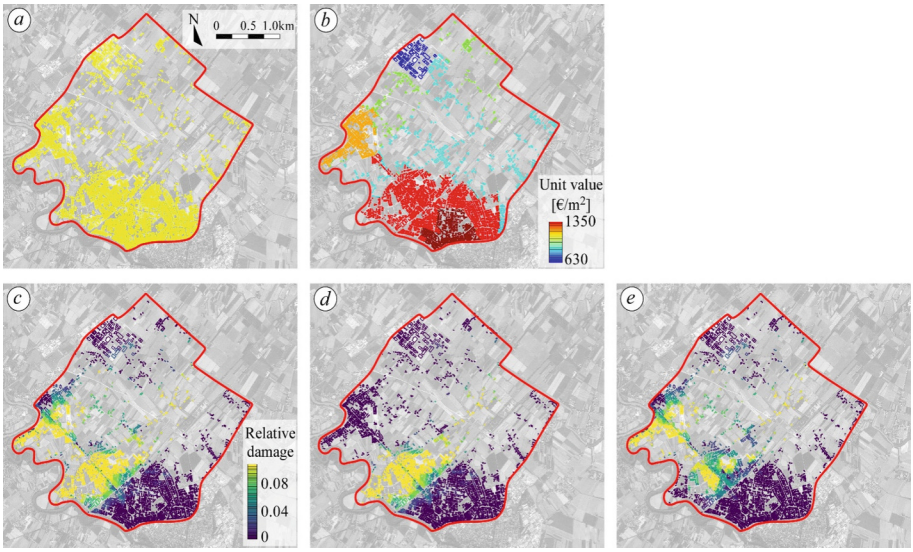

Fig. 4. Relative damage to buildings: (a) identification of building polygons from CTR; (b) evaluation of unit values; relative damage for the "as-is" (c), and the "planned" scenarios P1, P2 (d,e).

4.5 Damage to Industry

Damage to industry is also considered, accounting for economic losses associated with business interruption. In this study, damage to industry is estimated in terms of loss of daily revenues due to business interruption.

Assets are first identified within the hazard-impacted area by extracting polygons classified as *building* = *industrial* from the OSMAND database.

The economic loss associated to business interruption is quantified by estimating the average daily revenue for manufacturing activities (ATECO sector C) in the hazard-impacted area, according to data derived from the dataset of the Statistics Department of the Veneto Region, namely the Sistema Statistico Regionale. This value, subsequently combined with information derived from C.STAT (a data browsing platform designed by Unioncamere and the Guglielmo Tagliacarne Research Center of the Chambers of Commerce), is equal to 6,565 Euros per day (reference year 2021). Based on the average size of industrial buildings within the study area, this value is normalized to a unit value of 6.09 Euros/m^2/day.

Damage is then evaluated by combining hazard and exposure information. Given the high uncertainty associated with damage estimation, a conservative assumption is adopted by setting vulnerability equal to one. Consequently, only assets affected by flooding contribute to damage assessment (with relative damage equal to one), while unaffected assets are assigned zero damage, as illustrated in Fig. 5.

For the simulated event, the average flood duration is assumed to be 7 days, consistently for both the "as-is" and "planned" scenarios. Total damage is finally obtained by summing the contributions of industry units in the hazard-impacted area.

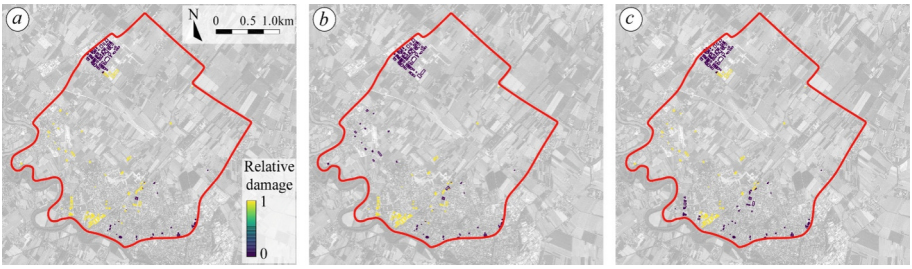

Fig. 5. Relative damage to industry for the "as-is" (a) and the "planned" scenarios P1, P2 (b,c).

4.6 Cost-Effectiveness Index

Total damages are determined for both the "as-is" and "planned" scenarios by summing the contributions evaluated in the previous steps and are reported in Table 1. Total damage is then calculated by considering a probability level equal to the return period of the hydrological event (i.e., 30 years). As previously mentioned, the total benefit is defined as $B = D_{as\text{-}is} - D_{planned}$, i.e., it is coincident with the avoided damage resulting from intervention implementation.

To determine the cost-effectiveness index, I_{CE}, it is necessary to estimating the intervention construction costs. In the present example, the levee reinforcement intervention has a length of approximately 230 m, corresponding to the extent of the considered breach. The unit cost per linear meter is estimated at 7,278.27 Euros/m, based on parametric evaluations derived from similar levee reinforcement works along the Piave River [43]. The resulting total construction cost is EUR 1,674,002.10. This value is the same for both the planned scenarios, as the present analysis compares alternative locations of the same intervention. However, for different types of interventions, construction costs may vary. Nonetheless, the proposed framework remains applicable.

Finally, the cost-effectiveness index is computed as the ratio between avoided damage B and construction costs C. The obtained values are EUR 16.75 and EUR 13.35 for the "planned" conditions P1 and P2, respectively. This indicates that, for every euro invested, approximately EUR 16.75 and EUR 13.35 of flood damages are avoided per single flooding event. Therefore, in this illustrative example, the intervention corresponding to scenario P1 is preferable, as it yields a higher index I_{CE}. This result reflects the lower residual damage associated with P1 compared to P2.

Table 1. Summary of estimated avoided damage, intervention cost, and probability, and benefit/cost ratio index for each scenario.

	"planned" scenario P1	"planned" scenario P2
$D_{as\text{ - }is}$	75,029,203.74 Euros	
$D_{planned}$	46,997,728.88 Euros	52,675,575.80 Euros
Probability	1/30 = 0.033	
B (avoided damage)	28,031,474.85 Euros	22,353,627.93 Euros
Length of the infrastructure	230 m	
Unit cost of the new structure	7,278.27 Euros/m	
C	1,674,002.10 Euros	
I_{CE} index	16.75	13.35

5 Conclusion

This study presented a rapid computational framework for estimating avoided flood damages in regional systems, with a specific application to levee breach scenarios along the Piave River in northern Italy. The framework integrates hazard assessment, exposure quantification, and vulnerability analysis to estimate both direct and indirect damages under “as-is” and “planned” conditions. The approach enables the evaluation of intervention benefits in terms of annualized avoided damages and provides a benefit index that can be effectively used to rank flood risk mitigation measures of different types and/or in different locations.

The application of the framework to a hypothetical levee reinforcement intervention demonstrated its capability to discriminate between alternative intervention locations, providing an objective and quantitative measure of expected benefits. In the presented example, the proposed intervention significantly reduced both direct damage to buildings and indirect losses for industrial activities. One location was clearly identified as preferable, yielding a higher benefit index and indicating greater economic efficiency.

Although tested on a single case study, the proposed framework is scalable and can be adapted to different flood-prone contexts and risk-mitigation interventions. It can provide, consequently, a valuable and easy-to-use DSS to support decision-making in regional flood risk management and policy design. Its flexibility allows the inclusion of multiple scenarios, alternative design solutions, and varying levels of data availability, making it particularly suitable for rapid and preliminary assessments of flood mitigation strategies.

Nonetheless, the limitations of the proposed framework should be mentioned: we focused primarily on direct damage to buildings and industry, and we assumed a fixed impact area. Compared to micro-scale approaches, which indeed requires extensive data availability, the adopted mass appraisal framework is less sophisticated due to data aggregation and the underlying simplifying assumptions. In addition, the results may be

sensitive to the choice of vulnerability (damage) functions, which needs further investigation. To further enhance the applicability of the proposed framework in integrated regional planning, future developments may be devoted to accounting for multiple hazards, cascading effects, and the full range of direct (e.g., to crops, livestock, infrastructures) and indirect (e.g., to industry and health) damages as well as intangible damages (e.g., psychological distress, loss of trust in authorities, impacts on cultural heritage and ecosystems) caused by flood events.

6 Disclosure of Interests.

The authors have no competing interests to declare that are relevant to the content of this article.

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