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SPECIAL ISSUE PAPER OPEN ACCESS

# A Micro-Scale Framework for Evaluating the Cost-Effectiveness of Building-Level Floodproofing Measures

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## ABSTRACT

The integration of building-level floodproofing into flood risk management frameworks is gaining increasing recognition. As property owners ultimately decide on implementation, and financial incentives can drive adoption, a critical gap remains: the absence of Building-Specific, Context-Sensitive, Micro-Scale Risk Assessment (BC\_MRA) frameworks that effectively support property owners and policymakers in their decision-making. This study introduces a BC\_MRA framework alongside a straight-forward yet expandable risk-based incentive structure, representing an innovative approach to enhancing property-level floodproofing, hereby advancing flood resilience research. A key contribution is a systematic methodology that contextualizes all the components of micro-scale flood risk assessment and the process for assessing the effectiveness of floodproofing interventions. The framework is applied to a case study in Pesaro, Italy, where dry and wet floodproofing strategies' financial viability and risk reduction potential are evaluated in response to riverine flood risk. Results underscore the importance of BC\_MRA to inform effective micro-scale flood mitigation, revealing that expected annual damage is not solely dependent on proximity to the river but is also significantly influenced by building-specific vulnerability to flooding. Furthermore, wet floodproofing consistently resulted in longer payback periods compared with dry floodproofing, rendering it economically unviable for any of the buildings studied.

## 1 | Introduction

As climate change and urbanization intensify flood risks, policymakers face the dual challenge of developing Flood Risk Management (FRM) strategies that are both effective and financially sustainable. In response, two parallel shifts have emerged within FRM. The first entails the integration of structural measures, non-structural strategies, and nature-based solutions to establish a more comprehensive and adaptive framework for

mitigating flood impacts (Anderson et al. 2022; Bezak et al. 2024; Du et al. 2020; Moon et al. 2024; van Berchum et al. 2019). Concurrently, a second shift has focused on addressing the social and economic dimensions of FRM by redistributing responsibilities among stakeholders across multiple spatial scales. This redistribution encompasses a spectrum of interventions, ranging from catchment-wide strategies to localized, property-level measures (Adedeji et al. 2024; Gersonius et al. 2008; Selsor et al. 2023). These shifts are increasingly reflected in

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contemporary flood resilience initiatives like *Integrated Flood Risk Management*<sup>1</sup> in Romania, which combines structural defenses with over 2000 targeted interventions, or the *Flood and Coastal Resilience Innovation Programme (FCRIP)*<sup>2</sup> in the UK, which integrates 10 different resilience actions, including property-level floodproofing, while engaging local stakeholders in decision-making.

Despite evidence from post-flood observations and studies demonstrating that floodproofing techniques—also known as property-level protection (PLP) measures—can significantly reduce flood damage and losses (Chung and Adeyeye 2018; de Moel et al. 2013; DEFRA 2016; Egli 2002; Kreibich et al. 2005; Poussin et al. 2015; Rehan et al. 2024; Thurston et al. 2008; Webber et al. 2021), data on their real-world performance remain limited (Aribisala et al. 2022). This gap in empirical evidence is especially problematic, as accurate damage assessments are crucial for evaluating the cost-effectiveness of these measures and guiding informed decision-making (Oliveri and Santoro 2000; Pistrika et al. 2014). While some initiatives, such as those by the New South Wales (Australia) government (EHG 2023), MiDAS (Alabbad et al. 2022), and RASOR (Arrighi et al. 2018) platforms or some other studies (de Ruig et al. 2020; Rehan et al. 2024) represent progress toward filling this gap, these efforts remain exceptions. Even when building-level resilience is addressed in such studies, the data granularity and flexibility needed to support the property owners in their decision-making are often insufficient. This underscores the need for enhanced methodologies that provide detailed, building-specific assessments to support informed decision-making both for property owners and policymakers (Adedeji et al. 2024; Rehan 2018).

In this context, the innovation presented in this paper lies in the development of a Building-Specific, Context-Sensitive, Micro-Scale Risk Assessment (BC\_MRA) framework that not only enhances the precision of riverine flood risk assessments at the property level but also integrates it with a risk-based incentive structure tailored to encourage the adoption of floodproofing measures. This integrated approach represents an innovative contribution to flood resilience research by advancing both the assessment technology and the socio-economic mechanisms that drive implementation.

The following sections build on this innovation by presenting the BC\_MRA framework as a practical and methodologically robust approach (Section 2) for conducting micro-level assessments of the efficiency of private floodproofing measures. The framework successfully integrates financial indicators and incentive structures to provide evidence-based insights for both property owners and policymakers. It systematically contextualizes the essential components required for such evaluations, including the refinement of synthetic flood damage curves by accounting for building conditions pre- and post-floodproofing, the development of cost estimation models, and the evaluation and integration of various types of incentive mechanisms (Cost-based, Performance-based, and risk-based) to support the adoption of floodproofing measures. The applicability and effectiveness of this framework are demonstrated through a case study in the city of Pesaro, Italy (Section 3). Key insights, limitations, and

future developments of this approach are widely discussed in Section 4.

## 2 | Methodology

The proposed methodology for a Building-Specific, Context-Sensitive, Micro-Scale Risk Assessment (BC\_MRA), as illustrated in Figure 1, unfolds in three phases: (1) the Contextual Decision-Making Foundation, which involves stakeholder collaboration to frame the context of the assessment, collect the input data, and identify the Decision Variables (DVs); (2) Initial and Floodproofed Risk Assessment, focusing on pre- and post-intervention risk evaluations; and (3) Final Measure Selection and Incentive Structure, aimed at developing floodproofing solutions and financial incentives for effective flood risk mitigation at the building level. Each of these steps is elaborated in the following section.

### 2.1 | Contextual Decision-Making Foundation

The initial phase of BC\_MRA methodology is dedicated to the collection of foundational data, the integration of contextual knowledge, and the identification of key DVs. This stage ensures a comprehensive, context-sensitive, and adaptable approach tailored to the specific requirements of flood risk assessment within the study area. To achieve this, the foundational data (hazard maps, exposure models, and damage function libraries) must adhere to rigorous standards to support micro-scale damage estimation and cost-benefit analyses. The specific criteria governing the selection and application of these datasets are elaborated in the subsequent subsections.

#### 2.1.1 | Hazard

In the context of BC\_MRA, it is essential to ensure that the complexity of the hydraulic model aligns with the requirements of the damage assessment approach (Apel et al. 2009; Sieg et al. 2023). Hazard models must provide highly detailed and accurate representations. Urban environments, in particular, demand two-dimensional hydraulic modeling to capture intricate flow pathways and interactions with built infrastructure (Costabile et al. 2020). These models rely on high-resolution digital elevation models (DEMs) to accurately simulate flood dynamics (Cook and Merwade 2009; Fatdillah et al. 2022; Sieg et al. 2023). Inadequate modeling can distort micro-scale damage assessments, leading to risk and damage misestimations (Komolafe et al. 2018; Olesen et al. 2017) that undermine its effectiveness in cost-benefit analyses for building-level measures.

#### 2.1.2 | Exposure

In flood risk assessment, exposure involves identifying and characterizing elements at risk and estimating their asset values. In this context, BC\_MRA requires object-based approaches for more precise flood damage estimation (Nofal et al. 2021;

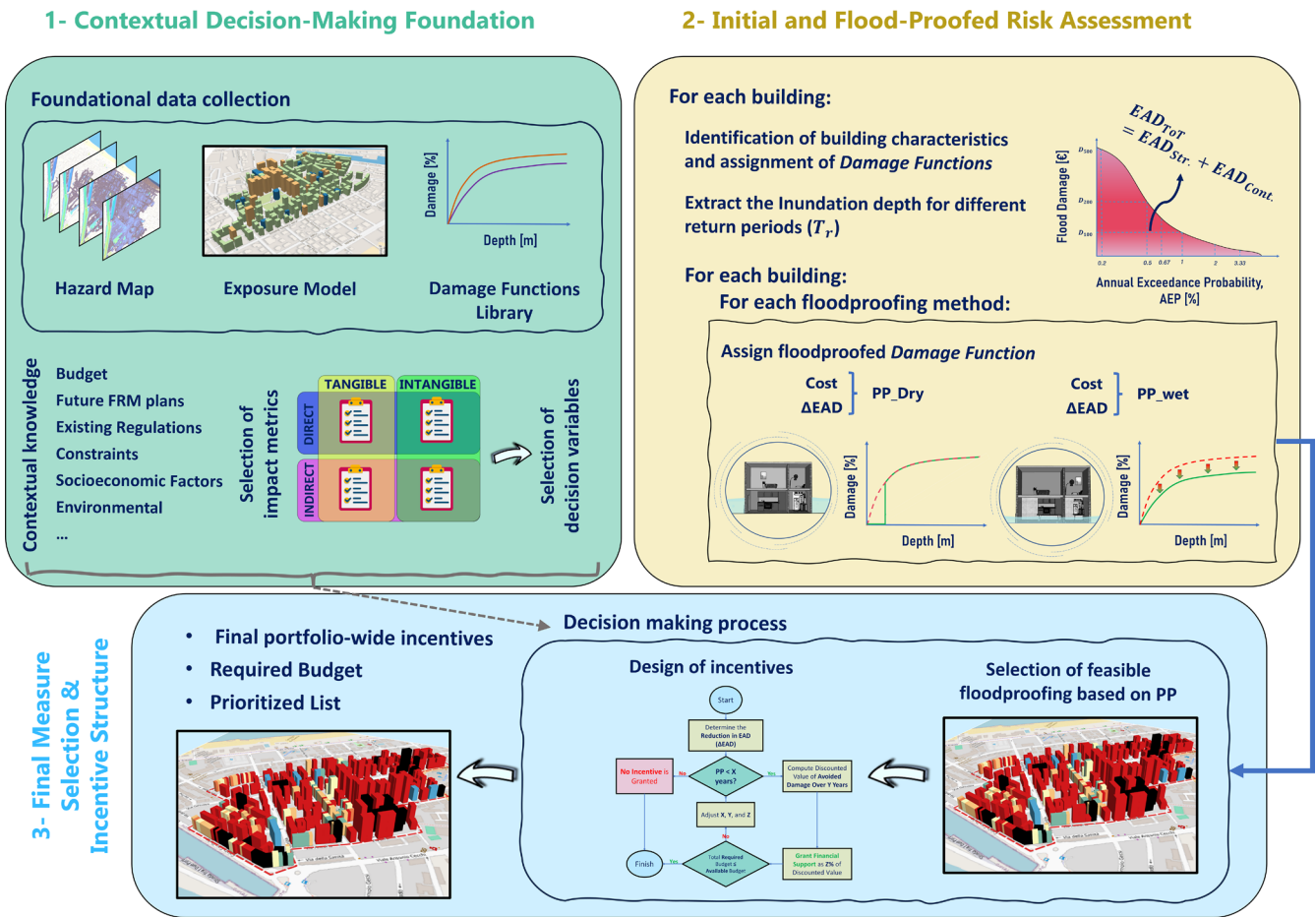


FIGURE 1 | Methodology framework and steps.

Röthlisberger et al. 2018). For this purpose, open-source datasets like OpenStreetMap (OSM) are commonly used (Sieg et al. 2019) but often lack completeness and precision, necessitating a multi-step refinement process to improve reliability (Pittore et al. 2017; Sieg et al. 2023).

Once exposure data is refined, buildings at risk must be categorized based on shared characteristics that influence their vulnerability to flooding (Oliveri and Santoro 2000; Oubennaceur et al. 2019; Pistrika et al. 2014). A systematic approach to this classification involves the use of building taxonomies, which group structures based on attributes relevant to flood damage (Dabbeek et al. 2020; De Angeli et al. 2016; Del Carlo et al. 2023). The selection of taxonomy attributes should be guided by two key considerations: first, ensuring compatibility with the input requirements of the damage model, and second, adapting the taxonomy to the local context to account for the diversity of building types in the study area (Mancini et al. 2017; McGrath et al. 2019; Merz et al. 2010; Oliveri and Santoro 2000; Pistrika et al. 2014).

### 2.1.3 | Damage Functions Libraries

Damage functions model the relationship between flood characteristics (e.g., flood type, inundation depth, velocity, duration, rise rate, sediment load, etc.) and the resulting flood-related impacts such as damage to buildings and their contents. Developing

a library of damage functions tailored to the unique characteristics of the study area, including flood type, building typologies, and assessment objectives, is an essential step in the BC\_MRA framework. To apply the methodology proposed in this paper, damage functions must be carefully selected based on their suitability for evaluating building-level floodproofing measures. Three fundamental aspects guide the selection of damage functions in this context: *granularity*, *flexibility*, and *transferability*.

The literature on flood damage modeling offers various classifications of damage functions, providing a comprehensive taxonomy of their characteristics and applications (Galasso et al. 2021; Marvi 2020; Merz et al. 2010). These classifications, along with the information provided in Table 1, serve as a guideline for selecting appropriate damage function models. Table 1 systematically filters options based on granularity, flexibility, and transferability. For instance, synthetic damage functions are preferred for their adaptability and ability to incorporate building-specific and floodproofed changes in attributes. Additionally, when context-specific absolute damage functions are unavailable, relative damage functions are preferred to improve transferability across different contexts.

### 2.1.4 | Content Damage

Content damage refers to the loss or destruction of movable items, such as personal belongings, equipment, and other

**TABLE 1** | Comparative assessment of damage function typologies in terms of granularity, flexibility, and transferability.

Criterion	Best-suited damage function typology	Rationale
Granularity	Micro-scale rather than Meso-scale	<ul style="list-style-type: none"> <li>• Capture specific building characteristics and the interaction of flood hazards with individual structures (Jongman et al. 2012; Santos et al. 2024).</li> <li>• Offer the necessary level of detail to rigorously assess the effectiveness of building-level floodproofing measures (Arrighi et al. 2021).</li> </ul>
Flexibility	Synthetic rather than Empirical	<ul style="list-style-type: none"> <li>• Can be developed either based on expert judgment (Dias et al. 2018; Pinos et al. 2020) or theoretical assumptions (Custer and Nishijima 2015; Figueiredo et al. 2021; Nofal and van de Lindt 2020; Porter et al. 2022) that can account for all nuance variability of the different components present in different exposures.</li> <li>• Can be used to assess floodproofing interventions in new or retrofitted buildings where historical data might be unavailable.</li> </ul>
Transferability	Synthetic rather than Empirical	<ul style="list-style-type: none"> <li>• Empirical models are less reliable, especially when transferring them to regions with different flood types or building characteristics (Amadio et al. 2019; Cammerer et al. 2013; Molinari et al. 2020; Sieg et al. 2023)</li> </ul>
	Relative rather than Absolute	<ul style="list-style-type: none"> <li>• Absolute depth-damage functions are sensitive to fluctuations in market values and inflation. Conversely, relative functions are more transferable across different spatial and temporal contexts (Appelbaum 1985; Krzysztofowicz and Davis 1983; Pistrika et al. 2014)</li> </ul>

non-structural assets inside a building (Davis and Skaggs 1992; HAZUS-MH 2024). While some building-scale studies overlook this aspect (Oubennaceur et al. 2019), accurately estimating content damage is a crucial step in BC\_MRA methodology, as it can impose severe economic burdens, fundamentally altering cost-benefit analyses. Beyond financial repercussions, these losses carry deep emotional and psychological consequences, shaping individual decision-making.

Three primary methodologies in the literature have been employed to incorporate content damage into flood risk assessments. Table 2 provides a comparative overview of these approaches, outlining their methodologies and inherent limitations. Content-Specific Damage Curves (Type III) is the most suitable approach to assess the cost-effectiveness of building-level floodproofing measures and is integral to our approach.

In our methodology, one critical consideration when employing Content-Specific Damage Curves is the estimation of content values across different building typologies, as the overall value of household contents varies significantly based on the size of the building and socioeconomic status (Appelbaum 1985; Sulong and Romali 2022). In a simplified manner, this valuation can be determined using Content-to-Structure Value Ratios (CSVR) (HAZUS-MH 2024). However, it is essential to note that CSVR values established in one context cannot be directly applied to others due to significant variations in building materials, construction practices, and regional characteristics. These factors influence property valuations, often rendering conventional ratios inadequate for cross-context application. This

paper proposes establishing context-specific content values by compiling a list of typical household contents and their associated costs. This approach accounts for variations in residential composition, building footprint sizes, and socioeconomic factors to ensure accurate content valuation. In the absence of detailed assessments, for the specific context of our case study in Italy, we propose using a CSVR range of 0.1 to 0.3, depending on socioeconomic conditions.

### 2.1.5 | Beyond Tangible Losses

Working at the microscale offers a unique opportunity to capture flood impacts that go beyond direct economic losses (Babcicky et al. 2021; Ten-Veldhuis and Clemens 2010; Thaler and Priest 2014). The high-resolution and context-sensitive nature of the BC\_MRA framework supports the identification and potential integration of intangible, non-financial impacts, such as the loss of emotionally significant items like memorabilia (Cantelli 2022; Sedighi et al. 2021), as well as broader psychological and social consequences (French et al. 2019; Law et al. 2025; Song et al. 2025).

Although such losses have been acknowledged for decades (Emrich et al. 2020; Green and Penning-Rowsell 1989; Johnson and Penning-Rowsell 2010), they are routinely excluded from conventional damage assessments due to their low economic measurability and methodological complexity, as their impacts are highly context-dependent and not easily transferable or generalizable across different settings (Ferri et al. 2020; Gabriels

TABLE 2 | Comparison of methods for assessing content damage.

Method	Approach	Limitations
I: Composite Damage Curves (Structural and Content)	Provide a collective estimate for both the building fabric and the contents (Huizinga et al. 2017)	<ul style="list-style-type: none"> <li>• Lacks specificity in separating content from structural damage.</li> <li>• May not accurately represent unique content loss characteristics for different property types.</li> <li>• Limited flexibility for detailed assessments requiring precise content valuations and cost-benefit analysis.</li> </ul>
II: Content Damage as a Percentage of Structural Damage	Estimate content damage as a proportional function of structural damage (Carisi et al. 2018)	<ul style="list-style-type: none"> <li>• Assumes a proportional relationship that may not hold true in all water depths.</li> <li>• Can be less accurate for properties with atypical content values or configurations.</li> <li>• Relies on pre-existing structural damage model, limiting standalone applicability.</li> </ul>
III: Content-Specific Damage Curves	Establish a relationship between the floodwater depth and the expected damage to building contents (Büchele et al. 2006)	<ul style="list-style-type: none"> <li>• Requires additional data collection and development of content-specific curves.</li> <li>• May need empirical data or expert elicitation, which can be resource-intensive.</li> <li>• Potential variability in accuracy based on the quality and representativeness of input data and assumptions.</li> </ul>

et al. 2022; Gnan et al. 2022; Rahim et al. 2023). However, recent literature increasingly recognizes that these impacts, particularly emotional distress, trauma, and the erosion of social support networks, can critically affect household recovery, especially for vulnerable groups like the elderly and females (Hudson, Botzen, et al. 2019; Lautrup et al. 2023; Mishra et al. 2022; Sakamoto et al. 2022).

Integrating these dimensions into risk assessments through stakeholder engagement, whether by eliciting qualitative insights or applying quantitative tools (Babcicky et al. 2021; Hudson, Pham, and Bubeck 2019; Sedighi et al. 2021; Ten-Veldhuis and Clemens 2010), can significantly enhance the completeness, relevance, and equity of flood resilience planning.

### 2.1.6 | Decision Variables

In the context of BC\_MRA, defining a set of contextual DVs is essential to capture the diverse priorities of various stakeholders. The existing literature on flood risk management presents a broad spectrum of DVs, each addressing distinct facets of the decision-making process (see, e.g., Du et al. 2020; Mortensen et al. 2024; Porter et al. 2022; Tascón-González et al. 2020). For an extensive discussion of these variables, readers may refer to FathiAzar et al. (2024).

To support informed decision-making across different stakeholder groups, this study identifies and categorizes relevant DVs according to their applicability and perspective, specifically for building owners and policymakers (Table 3). The first category includes DVs that can be directly incorporated into the BC\_MRA framework. These are primarily relevant to building owners, who prioritize the direct financial and property-related impacts of flood risks, seeking to minimize potential damages to their assets through cost-effective interventions. Such variables can be operationalized within the framework to enable micro-scale risk assessments. The second category consists of DVs that are more relevant for policymaking. Although these variables are influenced by building-level interventions and can be informed by the outputs of the BC\_MRA, they are not directly modeled within it. Policymakers operate at broader spatial and institutional scales that extend beyond the scope of a building-specific tool. Table 3 provides a comparative analysis of decision variables across two key stakeholder groups.<sup>3</sup>

## 2.2 | Initial and Floodproofed Risk Assessment

In the second phase of the BC\_MRA methodology, flood risk is assessed for both pre- and post-intervention conditions. The pre-intervention assessment establishes a baseline understanding of flood risk, providing a foundation for quantifying the effectiveness of proposed floodproofing measures. The choice of the risk (or impact) metrics depends on the study's objectives and can be expressed through various metrics (Farrag et al. 2022; Kron 2009; Müller 2013; Paudel et al. 2015).

In this study, the analysis was limited to direct tangible losses, specifically structural damage to buildings and damage to household contents. These losses were quantified using

**TABLE 3** | Comparative decision variables for stakeholders in micro-scale flood risk management.

Decision variables	Building owners	Policy-makers <sup>a</sup>
Effectiveness of floodproofing measures	✓	✓
Integration with larger structural measures		✓
Synergies between building-scale and structural measures		✓
Increased property value	✓	
(Re)insurance premiums (discounts for floodproofing)	✓	✓ <sup>b</sup>
Incentive structures for floodproofing	✓	✓
Non-insurable costs (clean-up, mental health)	✓	
Personal/sentimental value of contents	✓	
Injury or mortality risk		✓
Cost-effectiveness of mitigation measures: Payback Period (PP) <sup>c</sup> (ASTM 2020) or Benefit-to-Cost Ratio (BCR) (ASTM 2015)	✓	✓
Low probability/high damage events and public perception (Merz et al. 2009)		✓
Equity, systemic resilience, and regional prioritization		✓
Long-term social, economic, and environmental implications		✓

<sup>a</sup>The BC\_MRA framework can serve as a foundational input for a larger decision-making process. While it provides high-resolution, property-level data essential for localized decisions, it does not capture the full range of strategic, cross-sectoral implications necessary for policy planning. To ensure comprehensive and coordinated flood resilience strategies, policymakers must integrate insights from tools like BC\_MRA into broader frameworks that address synergies, trade-offs, and interdependencies across different scales and sectors.

<sup>b</sup>While reduced insurance premiums are often treated as a decision variable at the household level, this variable can also be leveraged by policymakers when government- or state-backed (re)insurance schemes, such as the UK's *Flood Re* (Penning-Rowsell 2015; Surminski and Eldridge 2017), are in place. Through the design and adjustment of these schemes, policymakers can influence insurance affordability and uptake, thereby shaping incentives for property-level flood resilience.

<sup>c</sup>A critical factor in this evaluation is the selection of an appropriate discount rate, which determines the present value of future flood risk reduction benefits (Truong et al. 2024). Given that floodproofing investments yield long-term benefits with a relatively low correlation to market volatility, a discount rate close to the *risk-free rate* is justified (Espinoza et al. 2020; Martello and Whittle 2023) and utilized in this framework.

Expected Annual Damage (EAD) as the primary risk metric. However, it is acknowledged that intangible and indirect impacts were not accounted for within the current framework. Although the inclusion of these aspects was considered beyond the scope of this work, their significance is recognized. It is therefore suggested that future research incorporate more

holistic evaluation approaches, such as multi-criteria decision analysis or stakeholder-informed valuation methods, to better capture the full spectrum of flood-related impacts at the household and community levels.

### 2.2.1 | Pre-Intervention

Mathematically, EAD is computed by integrating the product of the multivariate damage function  $D(d, v, t, \mathbf{B})$  and the joint probability density function for flood characteristics  $f(d, v, t)$  over the entire range of possible events; however, in most practical cases, flood hazard characteristics are provided in discrete intervals typically corresponding to specific mean return periods (e.g., 50-year, 100-year floods). In such cases, the continuous integration can be approximated by a summation, as shown in Equation (1).

$$EAD = \sum_{i=1}^N [P_{i-1} - P_i] \cdot \left[ \frac{D(d_{i-1}, v_{i-1}, t_{i-1}, \mathbf{B}) + D(d_i, v_i, t_i, \mathbf{B})}{2} \right] \quad (1)$$

Here,  $N$  represents the number of discrete levels or return periods;  $P_i$  is the probability of the flood event  $i$  that can be considered as the reverse of the return period.  $D(d, v, t, \mathbf{B})$  is the damage function that depends on the flood depth  $d$ , the velocity of the floodwater  $v$ , the duration of the flooding  $t$ , and the vector of building attributes  $\mathbf{B}$ , which can be represented by  $\mathbf{B} = (B_1, B_2, \dots, B_k)$ , where  $B_k$  represents a specific characteristic of the building (e.g., construction material, Area, etc.) which can influence how the building is impacted by the flood. In other words, vector  $\mathbf{B}$  personalizes the damage function for each single building (or building typology).

The process of calculating EAD begins with selecting the most appropriate damage functions ( $D$ ) from the library, both for building and content damages, ensuring they align with the building's specific attributes (vector  $\mathbf{B}$ ). Next, key flood hazard parameters, including inundation depth, flood velocity, and duration, are extracted from hazard maps for each return period and for each single building. These values are then used to compute the damage estimates for each return period. Finally, by applying Equation (1), the total EAD is derived, which is the sum of building EAD and content EAD.

Here, understanding the inundation process is fundamental for accurate flood risk assessments, as it directly impacts the evaluation of building vulnerability. Two critical factors must be considered in this process: the elevation of building entrances (or openings) and the presence of basements, each requiring distinct approaches and considerations. First, the elevation and location of building entrances play a critical role in determining the extent of inundation damage, as variations in entry points and surrounding terrain can significantly influence flood depth measurements. To ensure precision in flood risk evaluation, the door threshold and ground floor finished level should be measured at a consistent reference point, corresponding to the location where inundation levels were recorded. Automated or generalized statistical methods are deemed insufficient, as they fail to account for building orientation and spatial variations that affect flood exposure. Instead, a manual approach should be adopted to accurately

**TABLE 4** | Methodological approaches for evaluating dry and wet floodproofing impacts.

Approach	Methodology		Example
Direct Corrective Factors	Application of predefined reduction coefficients to the damage function	Dry Floodproofing	In the FLEMOps+ model (Thieken et al. 2008), reduction factors of 0.41 and 0.64 are applied to building and content loss, respectively. <sup>a</sup> Alabbad et al. (2022) applied a uniform reduction factor of 0.5 for both building and content damage.
		Wet Floodproofing	In the FLEMOps+ model, reduction factors of 0.64 and 0.85 are applied to building and content loss, respectively. <sup>b</sup> Alabbad et al. (2022) applied a uniform reduction factor of 0.8 for both building and content damage.
Indirect Corrective Factors	Damage functions for individual buildings are refined by adjusting generic curves based on vulnerability factors specific to each building	Dry Floodproofing	For instance, repairing plaster or repointing can lower an adjustment factor from 1.5 to 0.5 (Davis et al. 2023).
Modification of Depth-Damage Curves	Alteration of the damage function itself	Dry Floodproofing	Setting damages to zero below the floodproofing threshold (Gersonius et al. 2008; Nofal et al. 2021; Rehan 2018; Richert, Boisgontier, and Grelot 2019; <i>this study</i> ).
		Wet Floodproofing	Altering the damage curve based on the reduced vulnerability of the building after wet floodproofing ( <i>this study</i> ).

<sup>a</sup>Assuming dry floodproofing qualifies as a “very good precaution” measure and in cases without contamination.

<sup>b</sup>Assuming wet floodproofing can be classified as a “good precaution” measure and in cases without contamination.

determine reference points for extracting finished floor levels and water depth measurements, ensuring a more context-sensitive and reliable assessment of flood risk. Second, the presence or absence of a basement introduces additional complexity to the inundation process. For buildings without basements, water enters when the external water level surpasses entry points such as doors or window openings. For buildings with basements, however, water can infiltrate through multiple pathways, meaning that water level can rise internally from the basement upward.

### 2.2.2 | Post-Intervention

In the post-intervention risk assessment, the same evaluation method as pre-intervention is applied; however, the primary objective shifts to analyzing how floodproofing measures alter damage functions and, consequently, overall flood risk. The literature proposes several methodologies to quantify

floodproofing effects, broadly categorized into three groups: (i) direct corrective factors, (ii) indirect corrective factors, and (iii) detailed methods that directly modify depth-damage curves. Table 4 provides a structured comparison of these methodologies, outlining their underlying assumptions and examples from the literature.

The impact of floodproofing on damage functions is inherently depth-dependent (Richert, Erdlenbruch, and Grelot 2019). Consequently, the first two approaches, which apply uniform adjustments across the entire damage curve, are not well-suited for micro-scale evaluations. To achieve a more accurate and context-sensitive representation of damage reduction, this paper adopts the third approach, which involves modifying depth-damage curves.

For dry floodproofing, damage curve values are set to zero for flood depths up to the floodproofing height, beyond which they revert to their original levels. In contrast, for wet floodproofing, adjustments are made to the cost components associated with different

flood damage items, reflecting the extent of floodproofing and its effectiveness in reducing losses. Since wet floodproofing involves elevating certain appliances, content damage should be adjusted accordingly. In this paper, it is assumed that after wet floodproofing, content damage will decrease by 20% for inundation depths up to 0.2 m. Beyond this threshold, the effectiveness of elevating appliances as a mitigation measure diminishes, and the damage curve begins to converge with the original trajectory, fully aligning at 0.5 m and continuing along the same trajectory. Between 0.2 and 0.5 m, the sharp increase in damage reflects a critical point where the most elevated contents become submerged, leading to an accelerated loss rate despite prior protective efforts.

Once the building and content damage functions are modified for each single building and floodproofing method, the post-intervention EAD is calculated using the same approach as the pre-intervention EAD. The key distinction lies in updating the damage function  $D$  to reflect the floodproofing measures, replacing it with  $D_{\text{Dry}}$  for dry floodproofing and  $D_{\text{Wet}}$  for wet floodproofing.

### 2.2.3 | Cost of the Floodproofing

To assess the cost of floodproofing measures, the presented methodology uses the building perimeter as a key proxy for dry floodproofing cost estimation, as most interventions focus on sealing external structures to prevent water intrusion. In contrast, wet floodproofing costs are primarily influenced by total floor area and room functionality.

Existing studies reveal considerable variability in reported costs across regions and timeframes (Aerts et al. 2013; Keating et al. 2015; Kreibich et al. 2011). These discrepancies arise due to variations in local conditions and historical data, which, in turn, hinder the broader applicability (transferability) of such estimates (Aerts 2018). For instance, Paleo-Torres et al. (2021) indicate that dry floodproofing can increase construction costs by up to 25% in the U.S.; however, in the Italian context, costs are expected to be lower due to the high structural integrity of buildings, which generally require minimal reinforcement. Consequently, the primary expenses are associated with sealing measures rather than extensive structural modifications. In the proposed methodology, cost estimates are based on current market data, ensuring they reflect local conditions. Supporting Information 1 (SM1) provides some additional details on cost calculations.

## 2.3 | Final Measure Selection and Incentive Structure

Once the pre- and post-intervention EADs and implementation costs are calculated for each single building and for each floodproofing method, the Payback Period (PP) of the initial investment can be determined. The PP represents the time required for the reduction in EAD to offset the initial cost of the floodproofing measure. The floodproofing method with the shorter PP is considered the more cost-effective option for each individual building.

Since the decision to implement property-level floodproofing ultimately lies with individual homeowners (Rehan 2018),

effective financial incentives play a crucial role in encouraging adoption. Successful initiatives, such as the UK's *Partnership Funding Scheme* (DEFRA 2011), highlight how targeted financial aid from local authorities can significantly enhance the uptake of floodproofing measures. Designing an effective incentive mechanism for flood risk mitigation requires a structured approach that accounts for multiple critical factors. According to our methodology, there are four key components essential for developing such schemes.

### 2.3.1 | Incentive Structure

Incentives can be categorized into three primary models. *Cost-based incentives* provide financial support as a fixed percentage of the total investment, independent of the risk reduction achieved. While straightforward, this approach does not guarantee cost-effective outcomes. *Performance-based incentives*, by contrast, allocate funding contingent upon achieving predefined flood risk reduction targets, ensuring tangible benefits. Alternatively, *risk-based incentives* distribute financial support in proportion to the reduction in Expected Annual Damage ( $\Delta\text{EAD}$ ), thereby directly linking funding to quantifiable risk mitigation outcomes. This incentive model aligns with the approach adopted by the UK's Department for Environment, Food and Rural Affairs (DEFRA 2011).

### 2.3.2 | Incentive Allocation

The proportion of avoided damages covered by public funding is contingent on financial resources and budgetary constraints.

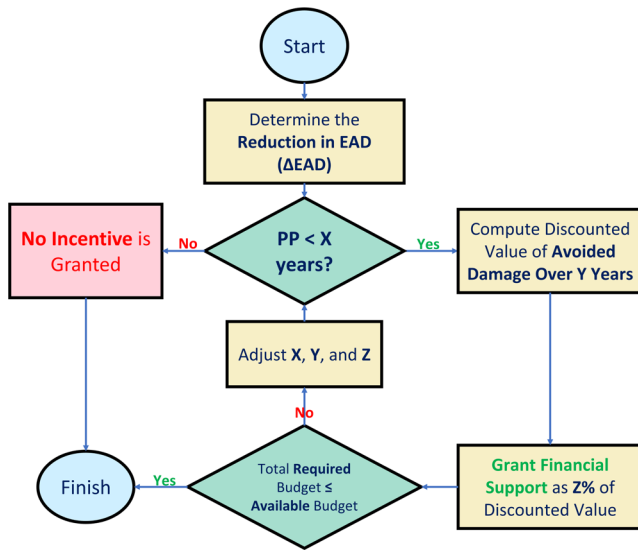
### 2.3.3 | Prioritization Strategy

Given financial limitations, prioritizing incentive distribution is crucial. This paper proposes ranking buildings based on the ratio of EAD from lower return periods to total EAD across all return periods. Buildings experiencing damage from frequent, lower-magnitude flood events should receive priority, as interventions in these cases yield more immediate and recurrent benefits.

### 2.3.4 | Incentive Disbursement Mechanisms

The mode of incentive distribution significantly influences the accessibility and effectiveness of risk mitigation measures. Homeownership status is a key determinant, as property owners are generally more inclined to invest in floodproofing compared with tenants (Richert, Boisgontier, and Grelot 2019). To extend adoption among rental properties, tax rebates or deductions for property owners investing in floodproofing could serve as a viable mechanism, aligning with existing financial models such as Italy's Seismic Bonus (Sisma Bonus) program (D'Alpaos and Bragolusi 2020).

Figure 2 presents an easy-to-implement flowchart for defining risk-based incentives while accounting for budget constraints. The total required budget can be estimated by first identifying



**FIGURE 2** | Risk-based incentive decision flowchart.

all floodproofed buildings with a payback period of less than  $X$  years. Next, the annual avoided damage for these buildings over the next  $Y$  years is discounted to its present value. Finally, the municipality provides financial support covering  $Z\%$  of this discounted amount. These parameters ( $X$ ,  $Y$ , and  $Z$ ) can be adjusted dynamically to ensure that the total sum of financial assistance does not exceed the available budget.

### 3 | Case Study

The case study is set in Pesaro, a city in the Marche Region, Italy, along the Adriatic Sea coast. It focuses on riverine flooding in the area at the outlet of the Foglia River, covering  $0.16\text{ km}^2$  and encompassing 377 residential buildings. The study area lies on the right-hand side of the river, where hydrodynamic conditions are characterized by relatively low flow velocity as the river transitions into its outflow towards the sea. The river itself features relatively large natural banks, which serve as the first line of defense against flooding. Beyond these banks, a relatively short flood wall has been constructed to provide additional protection to the adjacent urban areas.

In this study, certain assumptions are made to ensure a focused and practical analysis of floodproofing measures:

- The analysis focuses exclusively on residential buildings, while administrative, commercial, and educational buildings have been deliberately excluded. The decision variables for these types of buildings differ substantially, and a cost–benefit analysis based solely on structural and content damage would be misleading. Moreover, the availability of granular and reliable data for such occupancy types is limited, further justifying their exclusion from this study.
- The study does not consider damages to ancillary elements such as gardens, roads, vehicles, or car parks.
- This study considers only direct tangible losses, as the inclusion of intangible, indirect, and non-financial impacts

was not feasible due to the absence of direct stakeholder engagement.

## 3.1 | Data Collection and Input Parameters

### 3.1.1 | Hazard

The riverine flood hazard maps used in this study were provided by the CIMA Foundation, which originally developed them in collaboration with the Marche Region as part of the STREAM project (Strategic Development of Flood Management). The maps were generated using TELEMAC-2D, an open-source hydraulic model maintained by the Open TELEMAC-MASCARET<sup>4</sup> Consortium (Ata 2012; Hervouet 2007). TELEMAC-2D solves depth-averaged free surface flow equations (De St Venant 1871) using finite element methods on unstructured triangular grids. The model outputs, including water depth and depth-averaged velocity, were extracted at each computational node to support high-resolution flood risk assessment. To simulate flood hazard, peak discharge values for return periods of 5, 10, 20, 30, 50, 100, 150, 200, and 500 years were derived from the CIMA (2016) report, with standard-shaped design hydrographs generated using the Soil Conservation Service (SCS 1972) method. These hydrographs were used as input for TELEMAC-2D to produce flood hazard maps.

The DEM used for the simulation has a 1-m spatial resolution, ensuring fine-scale topographic representation. Additionally, the building layer from OSM was incorporated to capture interactions between flood dynamics and the built environment. These high-resolution inputs ensure that the hazard model meets the necessary spatial detail for micro-scale flood risk assessments. Figure 3 illustrates the spatial extent of flooding for six different return periods (30, 50, 100, 150, 200, and 500 years), along with the footprint of buildings and the designated area of interest.

### 3.1.2 | Exposure

To ensure a comprehensive assessment, this study includes neighborhoods experiencing varying levels of flood hazard, from frequent inundation zones (50-year floods) to areas that get inundated just by extreme flood events (200 and 500-year floods). The initial building footprints were extracted from OSM, forming the baseline dataset. To enhance accuracy, these footprints were cross-referenced and updated using official municipal maps from Pesaro's publicly available database.<sup>5</sup> An on-site field survey was then conducted to verify and refine the dataset, ensuring that the exposure model accurately reflects real-world building characteristics. The survey focused on collecting essential data derived from a combination of RETURN<sup>6</sup> taxonomy attributes (Lagomarsino et al. 2024) and INSYDE damage model parameters. Specifically, it allowed the collection of detailed data on the presence and type of basement and elevation levels of doors and windows, which were used to customize the damage and cost models for each building within the study area. Figure 4 provides a structured overview of these attributes, highlighting their sources and significance in estimating potential flood damage and floodproofing costs.

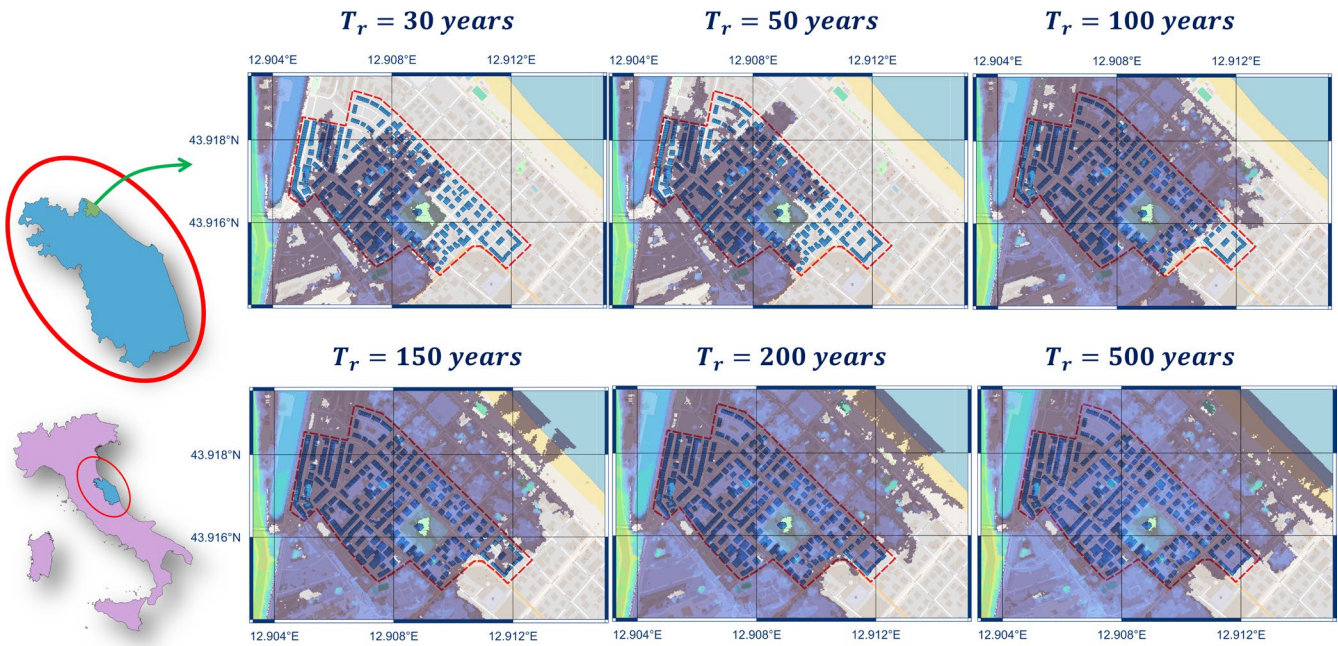


FIGURE 3 | Flood extent for different return periods.

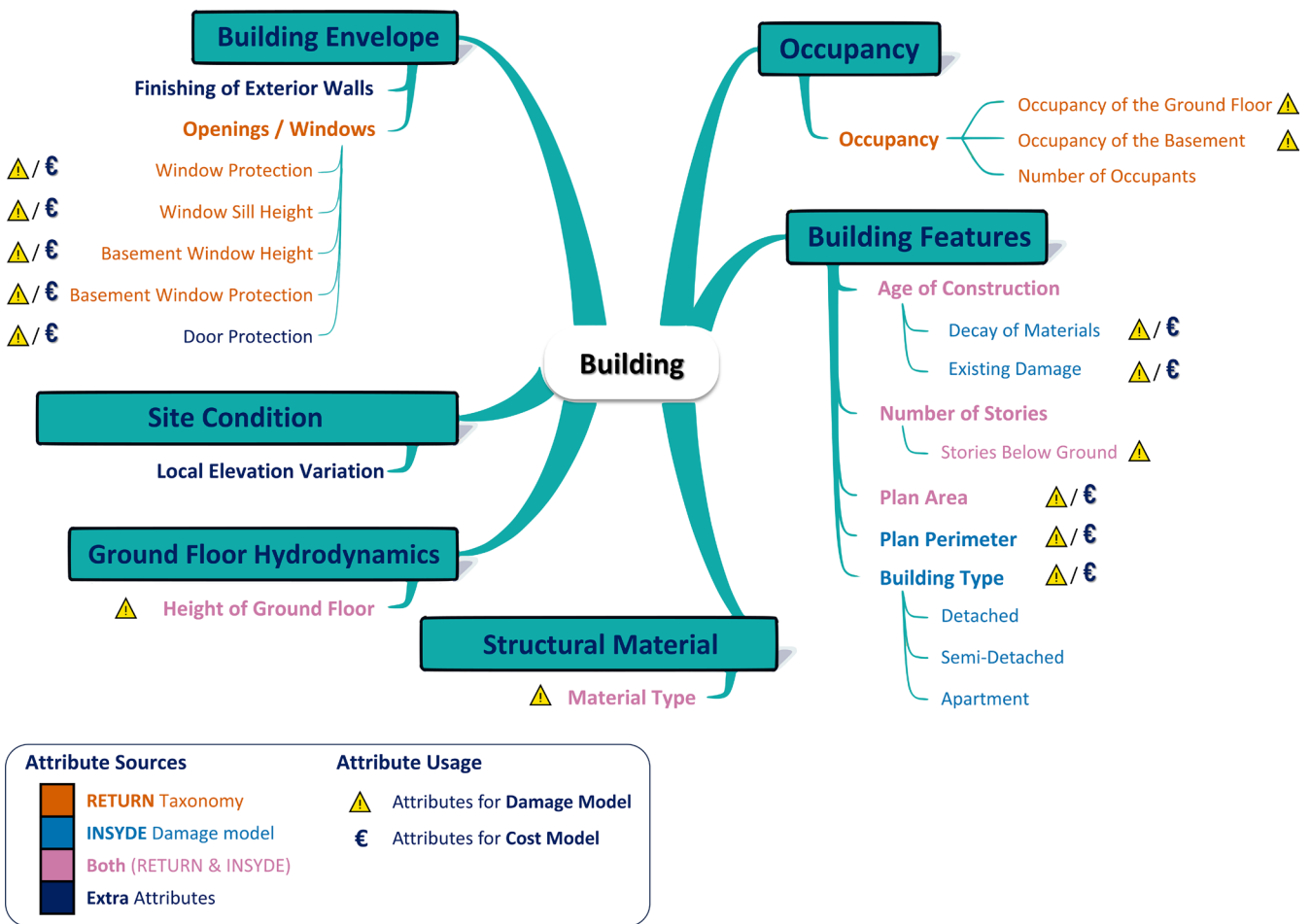
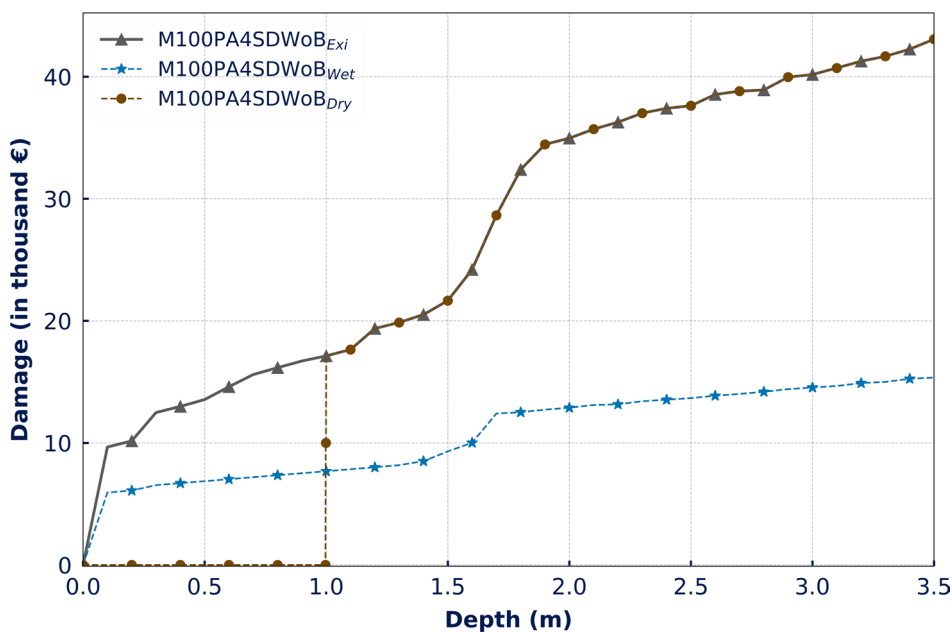


FIGURE 4 | Building attributes for exposure and cost modeling in flood risk assessment.



**FIGURE 5** | INSYDE-based damage curve for a 100 m<sup>2</sup> semi-detached masonry building (P/A=0.4, no basement).

### 3.1.3 | Damage Functions

The INSYDE (IN-depth SYnthetic Model for Flood Damage Estimation) model (Dottori et al. 2016) was employed in this case study. This synthetic model has been developed and rigorously validated across multiple case studies in Italy, proving its reliability and adaptability (Amadio et al. 2019; Molinari et al. 2020). The most influential parameter for INSYDE is water depth, as all the model's damage functions are directly dependent on it. Flow velocity and flood duration are also impactful parameters, but play a secondary role. The sensitivity analysis using the observed range of inundation depths (< 1 m) and velocities (< 0.5 m/s) for this case study indicated that the damage reported by the INSYDE model was not significantly influenced by water velocity. Therefore, only the inundation depth was considered in the analysis.

To improve the efficiency of flood damage assessment, this study proposes fixing some input variables in the INSYDE model and applying simplified rules and conversion factors. This allows for post hoc adjustments to depth-damage curves, ensuring they accurately reflect building-specific attributes, such as footprint area or perimeter-to-area ratio. These adjustments were derived through sensitivity analyses. Figure 5 illustrates a sample INSYDE-based damage curve for a semi-detached masonry building with a 100 m<sup>2</sup> area and a perimeter-to-area ratio of 0.4 without a basement. The curve compares the building's damage in its existing state and after implementing dry and wet floodproofing measures.

For interested readers, SM2 provides additional details on conversion rules and an overview of the most widely recognized damage models in Italy.

### 3.1.4 | Content Damage

In the presented case study, a mixed empirical-synthetic approach was adopted to convert the absolute content damage model proposed by Carisi et al. (2018) into a relative content

**TABLE 5** | Content value estimates for different residential building types and sizes.

Type	Footprint area (m <sup>2</sup> )	Content Value (€)		
		Lower bound	Upper bound	Average
Single Unit	Up to 100	15,000	34,000	24,500
	100 to 200	22,000	54,000	38,000
	More than 200	30,000	69,000	49,500
Duplex <sup>a</sup>	Up to 100	12,000	26,000	19,000

<sup>a</sup>In the case of duplex homes, as the prevalent footprint area is less than 100 sqm, it is assumed that the living room, kitchen, and dining room are situated on the ground floor, and the other rooms are on the second floor.

damage function. This damage curve applies to both the existing state of the building and after the implementation of dry floodproofing. However, for wet floodproofing, the damage curve was adjusted based on the method previously described. Additional details are provided in SM2.

Context-specific content values were derived by compiling a list of typical Italian household contents. Given that most buildings in the case study area have footprints smaller than 200 m<sup>2</sup>, content values were categorized into three size classes as presented in Table 5. Additionally, given the homogeneity of the socioeconomic condition of the area and its classification as a middle-income region, the average of the lower and upper content value bounds was used for analysis.

### 3.1.5 | Cost of the Floodproofing

Tables 6 and 7 present the average costs associated with dry and wet floodproofing across the various building typologies in the case

study area, calculated according to the methodology described in Section 2.2 and detailed in SM1. As outlined in the methodology, floodproofing costs were estimated using the building perimeter as the primary proxy for dry floodproofing, while the area was used to parameterize wet floodproofing interventions.

### 3.2 | Initial and Floodproofed Risk Assessment

#### 3.2.1 | Pre-Intervention

For each single residential building located within the defined study area, the most suitable backbone damage function was selected, followed by a post hoc modification to tailor the function to the specific characteristics of the building. Subsequently, hazard values for different return periods were extracted and used to calculate the net inundation depth for each structure. It is important to note that the algorithm for calculating inundation depth differs between buildings with and without basements, as it accounts for various potential water entry pathways, including both external and internal infiltration. Using Equation (1), the EAD was then computed for each building within the study area. While this study does not account for flood damage to storage and parking basements, the presence of a basement was incorporated into the inundation process calculations.

Regarding hazard value extraction, many buildings in the study area have multiple entry doors and are arranged in

**TABLE 6** | Cost estimates for dry floodproofing across various building types.

Building type	Perimeter (m)			
	Up to 40	40–60	60–80	80+
	Cost €/m			
Detached with basement	415	270	205	170
Semi-Detached (SD1) with basement	350	230	180	150
Semi-Detached (SD2) with basement	290	200	145	120
Detached without basement	250	170	135	115
SD1 without basement	225	155	125	110
SD2 without basement	210	140	110	90

**TABLE 7** | Cost estimates for wet floodproofing across various building types.

Building type	Area (m <sup>2</sup> )			
	Up to 100	100–200	200+	Duplex <sup>a</sup> Up to 100
	Cost €/m <sup>2</sup>			
Detached, Semi-Detached (SD1 and SD2) with or without basement	390	350	340	421

<sup>a</sup>Duplex homes require a distinct treatment, given that wet areas (such as kitchens and bathrooms) are predominantly located on the ground floor.

enclosed blocks with restricted access, often featuring parking areas or green gardens at a lower elevation than the surrounding streets. These elevation differences can lead to discrepancies in inundation depth measurements, as floodwater levels within these enclosed spaces may exceed those recorded on adjacent streets. To ensure precision, the door threshold and ground floor finished level were measured at a consistent reference point, corresponding to the location where inundation levels were recorded.

Figure 6 presents the distribution of EADs before implementing any floodproofing measures. It can be seen that flood risk is not exclusively determined by proximity to water bodies. Instead, it is significantly influenced by building-specific vulnerability and localized topography. Notably, some buildings exhibit high EAD values despite relatively low water exposure.

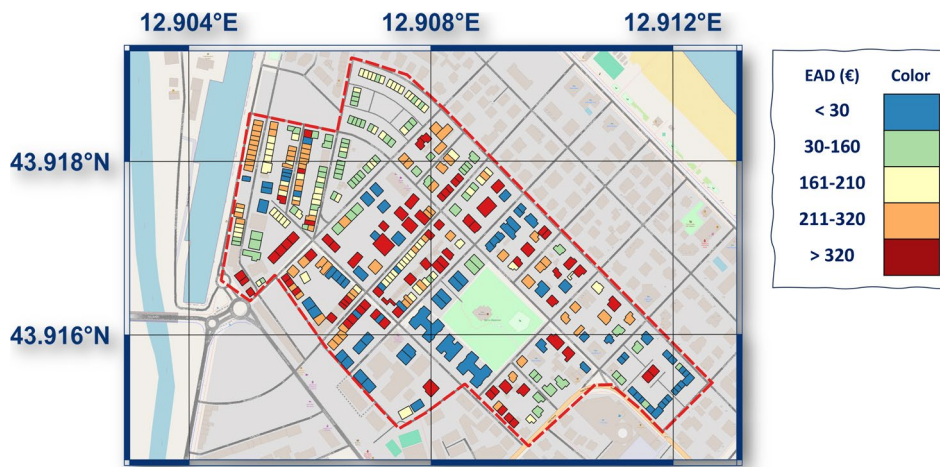
#### 3.2.2 | Post-Intervention

At this stage, the first step was to define the candidate floodproofing measures for each building within the study area. All buildings were considered for either dry or wet floodproofing, except those with residential basements, as habitable basements are highly susceptible to severe water damage and complete inundation. In such cases, dry floodproofing was the only viable flood protection measure.

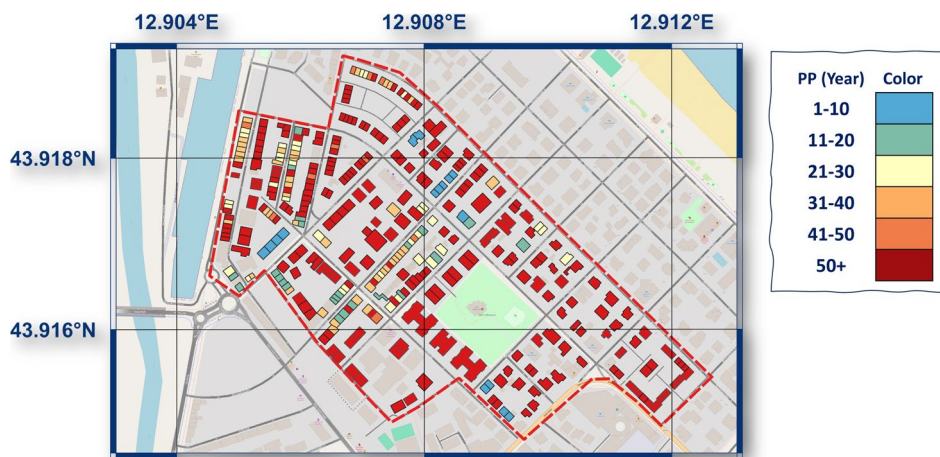
Then, for dry floodproofing, damage curve values were set to zero for flood depths up to 1 m (from street level), beyond which they revert to their original levels. Conversely, for wet floodproofing, modifications are applied to the cost components of various flood damage categories within the INSYDE model (Figure 5). SM2 provides a comprehensive comparison of original and adjusted unit costs in the INSYDE model while incorporating key assumptions on anticipated damage cost reductions from wet floodproofing interventions.

The modified damage functions for both building and contents were then used to calculate the EAD for each floodproofing method. The economic viability of these measures was subsequently assessed using the Payback Period (PP). For this evaluation, a risk-free discount rate of 3.6% was applied based on Italy's 10-year government bond yield as of January 31, 2025.<sup>7</sup> Figure 7 presents the PP values, with a maximum threshold of 50 years set for demonstration purposes.

The analysis indicates that wet floodproofing consistently results in longer PPs compared with dry floodproofing, rendering it economically unviable for any of the buildings studied. In contrast, dry floodproofing exhibits a wider range of PPs,



**FIGURE 6** | Spatial distribution of expected annual damage for residential buildings before intervention.



**FIGURE 7** | Expected payback period for floodproofing for individual buildings.

suggesting varying levels of financial feasibility across different properties. This outcome can be attributed to two key factors:

- First, the presence of a floodwall in the study area results in relatively low inundation levels, thereby reducing the economic viability of floodproofing. This interaction between structural flood protection measures and property-level floodproofing cost-effectiveness has long been recognized in flood risk management. Consequently, this study advocates for considering synergies between building-scale and structural measures as a decision variable (see Table 3). Such interactions should be carefully evaluated by policymakers and effectively communicated to property owners.
- Second, dry floodproofing demonstrates particular efficacy for buildings subject to frequent low-depth flooding due to the pronounced increase in damage within the first meter of inundation—a range where the damage curve exhibits the steepest incline (Poussin et al. 2015; Richert, Erdlenbruch, and Grelot 2019; Taramelli et al. 2022). However, wet floodproofing may be more suitable in alternative geographical or structural contexts where dry floodproofing is infeasible due to structural capacity to withstand flood pressure.

Finally, residential buildings with basements show the highest EAD and the shortest payback periods, indicating that such properties require special attention in future flood mitigation strategies.

While this study focuses on direct tangible losses, recent findings indicate that intangible impacts may range from one-quarter to twice the value of tangible damages (Hudson, Botzen, et al. 2019). Although these were not included here, this reported range could serve as a basis for sensitivity analyses, helping to approximate total flood-related losses and inform more targeted stakeholder elicitation. In practical terms, it enables the prioritization of buildings with the highest potential variation in payback periods for further elicitation, particularly under time or budget constraints.

### 3.3 | Incentive Structure for Floodproofing Measures

In this case study, interactions with stakeholders were not directly conducted, which limited the ability to fully assess potential budgetary constraints. However, by making reasonable assumptions for the parameters introduced in Figure 2 ( $X=50$  years,  $Y=20$  years, and  $Z=30\%$ ), the total required

budget is estimated at €241,517, allowing 66 buildings to receive financial support for the intervention.

In the future, we aim to improve this approach by incorporating direct stakeholder engagement to gain a better understanding of local priorities, financial constraints, and needs. This will help refine budget estimates and ensure that the proposed floodproofing measures align more closely with their expectations.

#### 4 | Conclusion

This study contributes to the themes of innovation and innovation management in the domain of flood resilience by introducing a novel framework: Building-Specific, Context-Sensitive, Micro-Scale Risk Assessments (BC\_MRA) framework. The approach aligns with emerging trends in the field, such as those exemplified by the *UK's Flood and Coastal Resilience Innovation Programme*, where funded projects increasingly integrate building-level interventions with broader resilience measures. However, this shift toward localized adaptation underscores a critical gap in the literature: the need for detailed, building-specific risk profiling and micro-scale cost-benefit analyses to inform targeted and effective mitigation efforts. Addressing this gap, the BC\_MRA framework offers a methodologically robust and contextually adaptive approach to support the design of tailored resilience strategies at the individual building level.

In parallel, the study addresses the management dimension of innovation by emphasizing the importance of context-sensitive implementation strategies, particularly given the central role of homeowners in adopting building-level flood resilience measures. Effective engagement at this scale requires individualized risk assessments and decision-support tools that incorporate a diverse range of building-specific and contextual variables to support informed and actionable decision-making. Building on this foundation, the study proposes a risk-based incentive structure and prioritization method that allocates financial support according to each building's specific risk profile and its potential for avoided damage. By linking funding levels directly to quantified risk reduction outcomes, this mechanism is designed to improve both the cost-effectiveness and fairness of floodproofing investments.

The paper first systematically examined the essential components of BC\_MRA by reviewing existing methodologies, identifying their limitations, and determining the most suitable approach. Through this analysis, the study critically assesses the essential characteristics that each component must possess to ensure accurate micro-scale damage assessments, preventing risk misestimation and distorted cost-benefit analyses. Specifically, it ensures that:

- The adopted hazard model integrates high-resolution DEMs and 2D hydraulic modeling to accurately capture flow pathways and interactions with the built environment.
- Exposure assessment follows an object-based approach, with buildings categorized using taxonomy-based classification.

The selected attributes align with damage model requirements while adapting to local building characteristics to enhance precision.

- Damage functions are carefully selected to ensure granularity, flexibility, and transferability. For building-level assessments, micro-scale, synthetic, and relative damage curves are prioritized. In assessing content damage, Content-Specific Damage Curves were prioritized. Given that content valuations vary by building size and socioeconomic status, a context-specific evaluation is conducted. In the absence of such data, we recommend a Content-to-Structure Value Ratio (CSV) ranging from 0.1 to 0.3 for the Italian context.
- The impact of floodproofing on damage functions is depth-dependent, rather than relying on uniform reduction factors, ensuring an accurate representation of intervention effectiveness.
- Cost estimations are adapted to local conditions, using building perimeter as a proxy for dry floodproofing costs and floor area for wet floodproofing costs, improving accuracy and applicability.
- The differences in pre- and post-floodproofing EADs were discounted to their present value using a risk-free discount rate.

The Pesaro case study offers several lessons that are potentially generalizable and transferable to other flood-prone urban contexts. First, the analysis highlights the crucial importance of collecting detailed, building-specific data (e.g., ground floor elevation, basement configuration, and door/window elevation) and utilizing an appropriate depth damage model to generate reliable damage estimates and cost-benefit assessments. The findings reveal that even buildings with comparable proximity to the river and similar hydraulic conditions (e.g., inundation depth and flood velocity) can exhibit markedly different risk profiles, owing to differences in their structural and functional attributes. Second, the spatial distribution of EAD before floodproofing indicates that flood risk is not solely determined by proximity to water bodies but is significantly influenced by building-specific vulnerability and localized topography. Finally, the study highlights how existing flood protection infrastructure (specifically, the flood wall along the river) influenced localized inundation patterns in adjacent built areas. As a result, even for buildings located near the riverbank, the residual flood risk was often too low to economically justify floodproofing interventions. This finding further reinforces the importance of accounting for the interactions among different flood risk management measures, an approach widely advocated in the existing literature on integrated flood risk governance.

In addition to the general lessons, several findings emerged that are specific to the local context of Pesaro. For instance, the analysis identifies dry floodproofing as a cost-effective mitigation strategy for certain properties, whereas wet floodproofing is economically unviable in this context. Buildings with residential basements exhibit the highest EAD and shortest payback periods, emphasizing the need for targeted flood mitigation

strategies for these structures. These findings collectively reinforce the necessity of BC\_MRA.

While the current study applies the BC\_MRA framework to riverine flooding, its structure is adaptable to other flood types, such as pluvial, coastal, or groundwater flooding. Each flood type presents specific hazard characteristics and impact mechanisms that require tailored modeling approaches. Exploring these adaptations could enhance the framework's broader applicability and utility. Future research should also expand beyond residential buildings to include other occupancy types, such as commercial properties, which require unique considerations due to the diverse business types and operational dependencies they entail. Additionally, greater attention should be given to intangible and non-financial flood impacts, which remain largely unaddressed in this study due to the absence of direct stakeholder engagement.

### Acknowledgments

The authors express their sincere gratitude to the CIMA Foundation for providing the detailed flood hazard maps that were instrumental in this study. The model was implemented through a collaboration between *Regione Marche* and the CIMA Foundation within the STREAM project (Strategic Development of Flood Management), part of the INTERREG Italy–Croatia V A 2014–2020 cooperation program. Open access publishing facilitated by Università degli Studi di Genova, as part of the Wiley - CRUI-CARE agreement.

### Data Availability Statement

Due to data-sharing restrictions, certain datasets, such as detailed flood hazard maps, are not publicly accessible. However, other datasets supporting the findings of this study are available upon reasonable request from the authors.

### Endnotes

<sup>1</sup> <https://inundatii.ro/en/> (Accessed June 6, 2025).

<sup>2</sup> <https://engageenvironmentagency.uk/engagementhq.com/innovation-programme> (Accessed June 6, 2025).

<sup>3</sup> <https://www.floodre.co.uk/> (Accessed June 6, 2025).

<sup>4</sup> <http://www.opentelemac.org> (Accessed June 6, 2025).

<sup>5</sup> <https://sit.comune.pesaro.pu.it> (Accessed June 6, 2025).

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### Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supporting Information. **Data S2:** Supporting Information.