

## Extended Partnership



*multi-Risk sciEnce for resilient commUnities undeR a changiNg climate*

**Spoke TS3** – Communities’ resilience to risks: social, economic, legal and cultural dimensions

**WP 7.2** – Innovative tools to evaluate risk mitigation effectiveness

**T 7.2.4** – Pilot cases

# Deliverable 7.2.4

## Pilot cases

Document versions:

<b>Authors</b>	<b>Actions</b>	<b>Date</b>
P. Asardis, M.P. Boni,	First drafting	Set 2025
P. Asardis, M.P. Boni, D. Ottonelli, F. Vigotti, S. Muratori	First drafting, completion, review and editing	Jan-Feb-Mar 2026
F. Vigotti, D. Molinari	Final review and approval	Mar 2026

## Table of contents

<b>1</b>	<b><i>Introduction</i></b> .....	<b>3</b>
<b>2</b>	<b><i>The modelling, simulation and analysis framework</i></b> .....	<b>5</b>
2.1	<b>General structure</b> .....	<b>6</b>
2.2	<b>Data requirements and input</b> .....	<b>6</b>
2.3	<b>Operational implementation of the framework</b> .....	<b>7</b>
2.4	<b>Methods</b> .....	<b>8</b>
2.4.1	Hazards-Impacts matrix.....	8
2.4.2	Win-Win criteria .....	8
2.4.3	Participatory process.....	8
<b>3</b>	<b><i>Proof of Concept (PoC)</i></b> .....	<b>15</b>
3.1	<b>Description</b> .....	<b>15</b>
3.2	<b>Risk reduction strategies</b> .....	<b>16</b>
<b>4</b>	<b><i>Results</i></b> .....	<b>22</b>
4.1	<b>Multi-risk reduction</b> .....	<b>22</b>
4.1.1	Individual well-being .....	22
4.1.2	Built environment.....	23
4.1.3	Business activities.....	24
4.1.4	Public services .....	25
4.1.5	Environmental systems .....	26
4.1.6	Communities .....	27
4.2	<b>Sustainable development</b> .....	<b>28</b>
4.2.1	Implementability .....	28
4.2.2	Reliability .....	29
4.2.3	Side impacts .....	29
4.3	<b>Priority score</b> .....	<b>30</b>
<b>5</b>	<b><i>Concluding remarks</i></b> .....	<b>33</b>
<b>6</b>	<b><i>References</i></b> .....	<b>34</b>

# 1 Introduction

In the context of the RETURN (*multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate*) project, the WP 7.2 – *Innovative tools to evaluate risk mitigation effectiveness* of the Spoke TS3 – *Communities' resilience to risks: social, economic, legal and cultural dimensions*, aims to establish national guidelines for evaluating the effectiveness of intervention alternatives in natural risk management, considering in detail Multi-Criteria Decision Analysis (MCDA) tools.

Deliverable 7.2.4 – *Pilot cases* – presents the application of a comprehensive methodological approach developed within WP 7.2 for the evaluation and prioritization of natural risk reduction strategies in territories exposed to multiple natural hazards and complex socio-economic pressures. The framework is designed to support decision-makers, civil protection authorities, municipalities, and local stakeholders in selecting interventions that are not only effective in reducing natural risks but also contribute positively to long-term sustainable development.

The proposed approach responds to a well-recognized limitation of current risk management practices, which often address hazards in isolation and relies on narrowly defined performance metrics (Hoang et al., 2018). In contrast, this Deliverable applies to an integrated MCDA framework capable of jointly assessing:

- reductions in expected impacts from multiple hazards,
- co-benefits and disbenefits associated with mitigation measures,
- intrinsic characteristics of interventions (e.g. costs, feasibility),
- stakeholder preferences and territorial priorities.

The framework is generic and modular, allowing its application across different geographical contexts and hazard combinations. Its operationalization is illustrated through a case study in the Lomellina area (Italy), exposed to both flood and seismic risk.

Natural hazards such as floods and earthquakes represent major threats to communities, infrastructure, and economic sectors. Recent events in Italy and across Europe have demonstrated that the impacts of such hazards are increasing, driven by climate change, urban expansion, and land use changes. In many regions, multiple hazards co-exist and affect the same exposed assets, creating complex risk profiles that cannot be adequately addressed through single-hazard approaches.

Despite advances in hazard and risk modelling, risk mitigation planning still largely relies on sectoral and hazard-specific methodologies. This leads to several shortcomings:

- limited understanding of synergies and trade-offs between measures addressing different hazards;
- insufficient consideration of territorial characteristics and socio-economic conditions;
- lack of transparency in how different objectives (e.g. safety, costs, sustainability) are balanced;
- weak integration of stakeholder values and preferences into technical assessments.

As a result, decision-makers often face difficulties in justifying and prioritizing investments, especially when measures perform well for one hazard but poorly for another (de Ruiter et al., 2021), or when risk reduction conflicts with social, economic, or environmental sustainability objectives (Curt et al., 2022).

While the primary goal of mitigation measures is the reduction of expected losses caused by hazardous events (FathiAzar et al., 2024), risk management interventions also shape territorial development pathways. Structural and non-structural measures can generate:

- social effects (e.g. changes in community cohesion, safety perception),
- economic impacts (e.g. investment costs, local economic stimulation),
- environmental consequences (e.g. land consumption, ecosystem alteration).

In this context, natural risk reduction and sustainable development are closely interconnected objectives (Ruangpan et al., 2024). However, they are characterized by different metrics, time horizons, and sources of uncertainty. This requires decision-support tools capable of integrating heterogeneous information, combining quantitative modelling outputs with qualitative expert assessments and stakeholder input.

## 2 The modelling, simulation and analysis framework

The proposed MCDA is implemented within a modelling, simulation, and analysis framework that enables a realistic representation of system behavior under multiple hazards. Within this framework, a predefined set of intervention alternatives (also referred to as “measures” in the following) is evaluated. Figure 1 illustrates the logical structure of the framework and its main components.

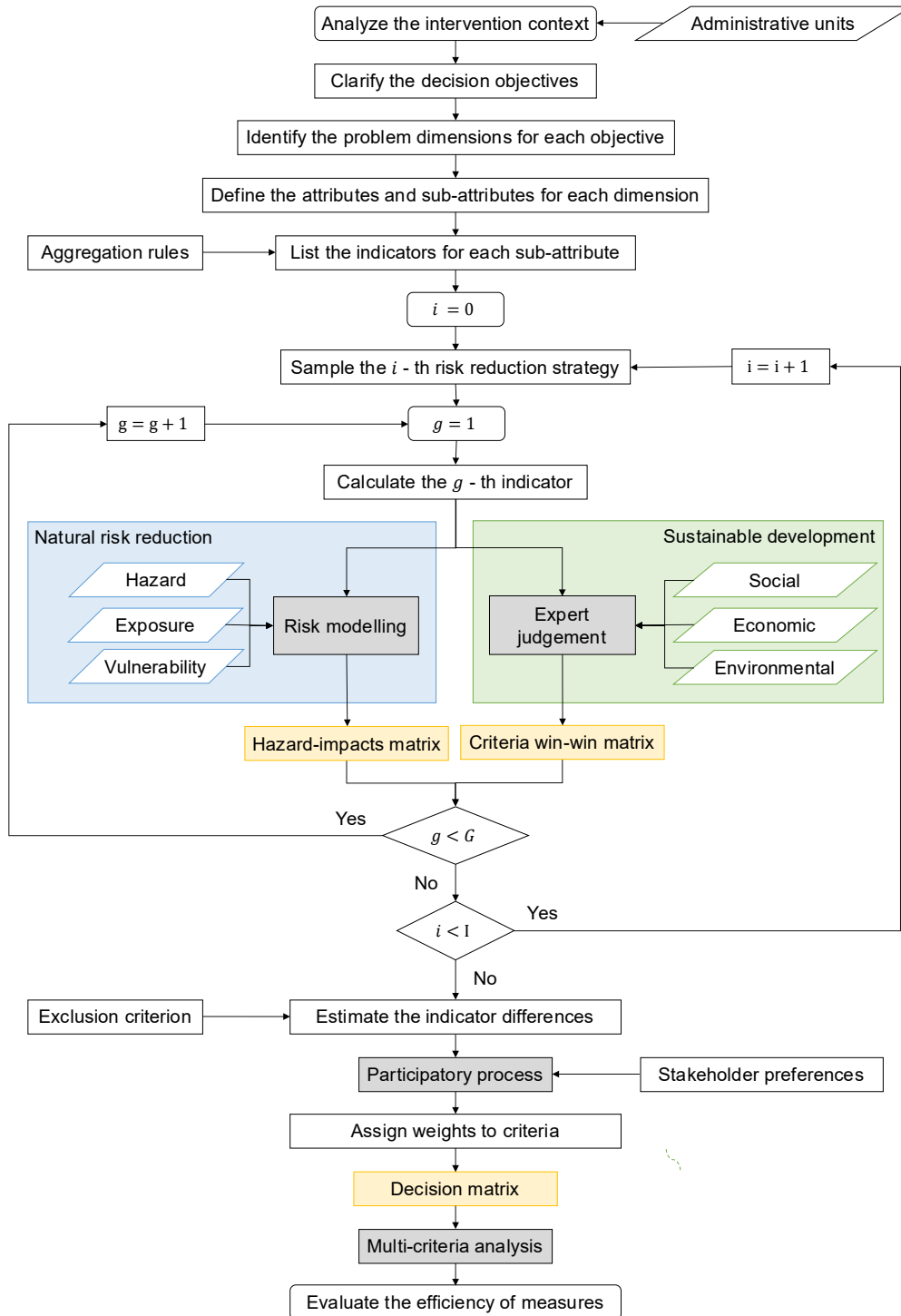


Figure 1. The modelling, simulation and analysis of the MCDA framework.

## 2.1 General structure

At a high level, the framework consists of four main building blocks:

1. Context and problem structuring, including the definition of objectives, dimensions, attributes, sub-attributes, and indicators;
2. Impact and risk modelling, used to quantify expected damage and risk reduction associated to the alternatives, for multiple hazards;
3. Sustainability assessment, based on technical and expert judgement to capture co-benefits, disbenefits, and intrinsic characteristics of measures;
4. Multi-criteria aggregation and ranking, incorporating stakeholder preferences through a participatory weighting process.

These components are fully integrated and iteratively applied to all intervention alternatives considered in the analysis.

## 2.2 Data requirements and input

Each application of the framework relies on a set of spatial, hazard-related, socio-economic, and expert-based datasets, summarized below.

### **Spatial and administrative context**

The geographical scope of the analysis is defined through administrative boundaries which delimit the spatial extent of regions, municipalities, or other relevant territorial units. These boundaries determine the aggregation level of indicators and the spatial resolution of modelling outputs.

### **Risk reduction strategies**

The set of intervention alternatives  $i = 1, \dots, I$  includes both structural and non-structural measures, such as engineering works, relocation policies, or planning tools. Each strategy is described through its technical characteristics and implementation requirements.

### **Hazard, exposure, and vulnerability data**

Natural hazards are characterized by input data describing their frequency and intensity. These include, for example, the inundation area and water depth in the case of floods, the peak ground acceleration for earthquakes, and the probability of exceedance associated with a given return period. Exposure elements include population, buildings, economic activities, and critical infrastructures, all of these categorized into the seven classes of the matrix hazards-impacts: individual well-being, built environment, business activities, public services, environmental systems, communities and financial system. Vulnerability information captures the susceptibility of exposed elements to damage, based on physical, functional, or socio-economic properties.

### **Impact and sustainability factors**

Impact models are selected according to hazard type and scale of analysis, including parametric models, exposure assessments, damage functions, fragility curves, and input-output approaches. In parallel, sustainability factors are analyzed through technical and expert-based assessments of:

- social effects (e.g. social cohesion, equity),
- economic effects (e.g. investment and maintenance costs),
- environmental effects (e.g. land use, pollution).

## 2.3 Operational implementation of the framework

### Structuring objectives and evaluation criteria

The decision problem is structured hierarchically:

- Decision objectives represent high-level goals (natural risk reduction and sustainable development);
- Problem dimensions describe key aspects of each objective;
- Attributes and sub-attributes translate dimensions into sub-components;
- Indicators provide quantitative or qualitative metrics for attributes' evaluation.

This hierarchical structure ensures transparency and traceability between strategic objectives and operational indicators.

### Simulation of intervention scenarios

The intervention alternatives are simulated by modifying hazard, exposure, or vulnerability data, and their performance is assessed in terms of both risk reduction and sustainability effects.

### Assessment of natural risk reduction

For each intervention alternative, including the “do nothing” alternative, the framework performs a simulation that estimates the expected value of impacts for all relevant hazards. Hazard, exposure, and vulnerability data are fed into the selected impact models to compute the Expected Annual Damage (EAD).

The overall risk indicator is calculated probabilistically as the sum of EADs for the different  $n = 1, \dots, N$  natural hazards affecting the study area:

$$EAD = \int_0^1 D(p) dp$$

where  $p$  denotes annual exceedance probability and  $D(p)$  damage associated with the event that has probability  $p$ .

This formulation allows a consistent comparison of baseline (i.e. the “do nothing” alternative) and intervention scenarios and supports the estimation of risk reduction attributable to each measure.

### Assessment of sustainability effects

In parallel with risk modelling, sustainability-related effects are assessed using a structured evaluation matrix guided by predefined criteria. This step captures characteristics and side impacts of measures that can be modeled quantitatively or qualitatively, such as social acceptance, cultural effects, or long-term environmental consequences. Qualitative analysis is supported by territorial information to ensure consistency and relevance.

### Indicator differences and exclusion criterion

For each indicator, differences between the baseline and intervention scenarios are computed. Indicators that do not vary across alternatives are excluded from further analysis, ensuring that only discriminating criteria influence the final ranking.

### Stakeholder participation and weighting

Stakeholder preferences are elicited through a participatory process. Stakeholders assign relative importance to attributes and objectives, reflecting local priorities and values. Weights are normalized and stored for use in the aggregation phase.

### **Aggregation and ranking of alternatives**

The weighted sum method is applied to compute efficiency scores for each attribute and objective. Final scores represent the overall performance of each intervention alternative, combining risk reduction effectiveness and sustainability contributions.

### **Expected outputs and decision support value**

The framework produces:

- a ranked list of intervention alternatives,
- transparent documentation of assumptions, weights, and criteria,
- quantitative and qualitative evidence supporting decision-making.

These outputs support authorities and stakeholders in prioritizing interventions that enhance resilience to multiple hazards while promoting sustainable and efficient use of resources.

### **Applicability and limitations**

The framework is designed to be flexible and scalable. It can be applied to real-world case studies or virtual testbeds and adapted to different hazard combinations. While the current implementation focuses on floods and earthquakes and does not model hazard interactions, the structure allows future extensions as data and modelling capabilities improve.

## **2.4 Methods**

### **2.4.1 Hazards-Impacts matrix**

The natural hazard impacts on individual well-being, built environment, business activities, public services, environmental systems, and communities are evaluated by using the Hazards-Impacts matrix. More details are supplied in Deliverable 7.2.2.

### **2.4.2 Win-Win criteria**

The co-benefits and disbenefits of the measures, as well as their characteristics, are evaluated by referring to the Win-Win criteria. More details are supplied in Deliverable 7.2.3.

### **2.4.3 Participatory process**

Stakeholder participation is adopted to elicit preferences and to assign weights to the evaluation of attributes defined within the MCDA framework (Figures 2–3). In MCDA, weights express the relative importance of attributes in the aggregation model and should not be interpreted as absolute measures of importance; rather, they reflect stakeholders' value judgements and priorities that are context-dependent and should be elicited with explicit reference to the decision problem and to the meaning of each attribute in the assessment. For this reason, the weighting phase must be implemented through a structured participatory process aimed at ensuring transparency, legitimacy, and practical relevance of the resulting configuration.

In the Lomellina case study, the participatory weighting exercise consisted of two dedicated workshops:

- **Workshop 1:** hosted and organized by CIMA in Savona, Italy, involving a broad set of stakeholders. Participants primarily included key actors of the Civil Protection system (regional staff and volunteers), as well as representatives of local institutions (e.g., Regione Liguria, GAL

Risorsa Lomellina). Project researchers also took part to support facilitation and ensure a shared interpretation of the attributes. This workshop focused on ranking and weighting attributes related to risk modelling, used to quantify reductions in expected impacts from multiple hazards (Figure 2).

- **Workshop 2:** held in Mede, seat of the Local Action Group “Risorsa Lomellina”, involving local representative stakeholders of the case study context (Civil Protection volunteers, consortia, practitioners). The workshop focused on ranking and weighting “win-win” criteria (Figure 3), with two separate elicitation exercises carried out for: (i) co-benefits and disbenefits and (ii) intrinsic characteristics of mitigation measures.

To elicit preferences in an intuitive and low-burden way for heterogeneous stakeholder groups, the card-based ranking method proposed by Simos (1989; 1990) was adopted. Participants, divided into working groups, received a set of cards representing the attributes and were asked to express preferences qualitatively by ordering the cards rather than assigning numerical weights directly. Each card also reported the expected range of the corresponding attribute for the Lomellina case study (i.e., the maximum variation observed across the intervention alternatives considered), to support a consistent interpretation of its meaning and potential influence on the assessment. This approach supports dialogue, reduces cognitive effort, and is well suited to participatory settings, while still allowing the computation of quantitative weights. Moreover, it supports the generation of multiple alternative weighting sets, enabling robustness analyses and comparisons across groups (Figueira et al., 2005).

For both workshops, the ranking task followed the same steps:

1. Sorting into classes of importance: each group was first asked to group the cards into three classes (high/medium/low) based on perceived relevance in the decision context.
2. Ordering within classes: groups refined the ranking by ordering attributes within each class; ex-aequo positions were allowed when participants considered attributes equally important.
3. Blank cards: one or more blank cards could be inserted between two consecutive attributes (or between importance classes) to represent larger perceived differences in importance; the higher the number of blank cards, the larger the intended gap in weights.
4. Plenary discussion: each group presented its ranking, and differences were discussed to clarify assumptions and interpretations.

In the second workshop, an additional and simplified elicitation step was included to capture the relative importance of the three categories of attributes adopted in the framework: (i) risk modelling, (ii) co-benefits and disbenefits, and (iii) characteristics of measures. Groups were asked to assign a reference score of 10 to the “risk modelling” category and scores from 1 to 10 to the other two categories, expressing their perceived relevance compared to the primary objective of reducing risk and expected impacts. The resulting scores (by group) are reported in Table 10.

Workshop 1 was conducted with four parallel working groups, while Workshop 2 involved two groups due to the limited number of participants. The exercise produced one attribute hierarchy per group, which constituted the basis for subsequent weight computation. Group rankings resulting from the two participatory processes are summarized in Table 1 (Workshop 1) and Tables 3–4 (Workshop 2). Please note that, consistently with the framework implementation described in the following sections, the results reported here (rankings and weights) refer to the subset of attributes retained for the case study application, i.e., those effectively used to discriminate across the intervention alternatives (see the exclusion criterion discussed in Section 2.3).

After the workshops, the card rankings were converted into numerical weights. Two alternative aggregation approaches were tested to derive a final set of weights from group results:

- **Approach 1 (group-based computation and averaging):** weights were computed separately for each group hierarchy and then aggregated (by averaging) to obtain a single final weight vector.
- **Approach 2 (shared hierarchy computation):** a single consolidated ranking was first derived by comparing the attribute positions across groups (via pairwise comparisons of positions), and weights were computed directly from this shared hierarchy. This comparative analysis is presented in Table 2 (Workshop 1) and Tables 5–6 (Workshop 2).

The consolidation of group rankings into a shared hierarchy under Approach 2 differed across the two workshops. For Workshop 2, it was straightforward because the two group rankings were highly consistent and, for the attributes related to measure characteristics, largely coincident, with limited ambiguity. For Workshop 1, deriving a consolidated hierarchy required more reconciliation due to greater dispersion across the four group rankings and because some groups were unable to complete the ordering of attributes within each class due to time constraints. Despite these practical challenges, Approach 2 was adopted for subsequent implementation because it provides a single, explicitly documented hierarchy and improves transparency in how differences across groups are reconciled into a shared preference structure. This approach also allows the weighting procedure to be applied once, rather than repeated for each group.

Table 1. Group rankings of the attributes related to risk reduction, from Workshop 1

IMPORTANCE CLASS	GROUP 1	GROUP 2	GROUP 3	GROUP 4
<b>High</b>	1. Damage to residential assets 2. Affected people 3. Impact on secondary sector; Damage to agricultural assets 4. Disruption of transport services 5. Impact on atmosphere	1. Affected people 2. Disruption of transport services 3. Damage to lifelines 4. Damage to residential assets 5. Damage to agricultural assets 6. Impact on primary sector	1. Affected people	1. Affected people; Impact on atmosphere 2. Damage to lifelines; Damage to agricultural assets; Damage to residential assets 3. Impact on secondary sector; Impact on primary sector
			<i>BLANK CARD</i>	
<b>Medium</b>	6. Damage to industrial assets; Damage to lifelines; Impact on tertiary sector; Impact on primary sector; Disruption of recreational services; Impact on cultural capital 7. Costs	7. Impact on atmosphere 8. Impact on surface hydrosphere 9. Disruption of recreational services 10. Impact on secondary sector 11. Impact on tertiary sector 12. Damage to commercial assets 13. Damage to industrial assets 14. Costs	8. Damage to residential assets	4. Costs; Damage to industrial assets
			<i>BLANK CARD</i>	<i>BLANK CARD</i>
			9. Impact on primary sector	5. Indirect physical damage; Disruption of transport services
			10. Disruption of recreational services; Impact on cultural capital	<i>BLANK CARD</i>
			11. Costs	6. Impact on surface hydrosphere
			12. Impact on surface hydrosphere	
	-	<i>BLANK CARD</i>	-	-
<b>Low</b>	8. Impact on surface hydrosphere; Indirect physical damage; Damage to commercial assets	15. Indirect physical damage 16. Impact on cultural capital	13. Damage to commercial assets	7. Damage to commercial assets; Impact on tertiary sector
			14. Damage to industrial assets 15. Damage to lifelines	<i>BLANK CARD</i>

IMPORTANCE CLASS	GROUP 1	GROUP 2	GROUP 3	GROUP 4
				8. Impact on cultural capital; Disruption of recreational services

Table 2. Pairwise comparison of positions across the group rankings, supporting the derivation of the shared hierarchy under Approach 2 for the attributes related to risk reduction (Workshop 1). Class rank refers to the position of each attribute within its importance class (e.g., 1/5 indicates the first attribute out of five within that class).

ATTRIBUTE	GROUP 1			GROUP 2			GROUP 3			GROUP 4		
	Class	Class rank	Overall rank	Class	Class rank	Overall rank	Class	Class rank	Overall rank	Class	Class rank	Overall rank
Affected people	High	2/5	2	High	1/6	1	High	1/7	1	High	1/3	1
Damage to residential assets	High	1/5	1	High	4/6	4	Medium	1/5	8	High	2/3	2
Damage to agricultural assets	High	3/5	3	High	5/6	5	High	4/7	4	High	2/3	2
Impact on atmosphere	High	5/5	5	Medium	1/8	7	High	2/7	2	High	1/3	1
Disruption of transport services	High	4/5	4	High	2/6	2	High	6/7	6	Medium	2/3	5
Impact on secondary sector	High	3/5	3	Medium	4/8	10	High	7/7	7	High	3/3	3
Damage to lifelines	Medium	1/2	6	High	3/6	3	Low	3/3	15	High	2/3	2
Impact on primary sector	Medium	1/2	6	High	6/6	6	Medium	2/5	9	High	3/3	3
Impact on tertiary sector	Medium	1/2	6	Medium	5/8	11	High	5/7	5	Low	1/2	7
Disruption of recreational services	Medium	1/2	6	Medium	3/8	9	Medium	3/5	10	Low	2/2	8
Damage to industrial assets	Medium	1/2	6	Medium	7/8	13	Low	2/3	14	Medium	1/3	4
Costs	Medium	2/2	7	Medium	8/8	14	Medium	4/5	11	Medium	1/3	4
Impact on surface hydrosphere	Low	1/1	8	Medium	2/8	8	Medium	5/5	12	Medium	3/3	6
Indirect physical damage	Low	1/1	8	Low	1/2	15	High	3/7	3	Medium	2/3	5
Impact on cultural capital	Medium	1/2	6	Low	2/2	16	Medium	3/5	10	Low	2/2	8
Damage to commercial assets	Low	1/1	8	Medium	6/8	12	Low	1/3	13	Low	1/2	7

Table 3. Group rankings of the attributes related to co-benefits and disbenefits of the measures, from Workshop 2

IMPORTANCE CLASS	GROUP 1	GROUP 2
<b>High</b>	1. Impact on community cohesion 2. Impact on cultural heritage 3. Changes in cultural landscape	1. Impact on community cohesion 2. Impact on cultural heritage; Changes in cultural landscape
<b>Medium</b>	4. Impacts on social equity and justice <i>BLANK CARD</i>	3. Impact on trust between institutions and community; Impacts on social equity and justice

IMPORTANCE CLASS	GROUP 1	GROUP 2
	5. Impact on trust between institutions and community	
Low	6. Land consumption	4. Land consumption

Table 4. Group rankings of the attributes related to intrinsic characteristics of the measures, from Workshop 2

IMPORTANCE CLASS	GROUP 1	GROUP 2
High	1. Performance under uncertainty	1. Performance under uncertainty; Engagement of stakeholders
Medium	2. Engagement of stakeholders	-
Low	3. Ease of maintenance	2. Ease of maintenance

Table 5. Pairwise comparison of positions across the group rankings, supporting the derivation of the shared hierarchy under Approach 2 for the attributes related to co-benefits and disbenefits of the measures (Workshop 2).

ATTRIBUTE	GROUP 1			GROUP 2		
	Class	Class rank	Overall rank	Class	Class rank	Overall rank
Impact on community cohesion	High	1/3	1	High	1/2	1
Impact on cultural heritage	High	2/3	2	High	2/2	2
Changes in cultural landscape	High	3/3	3	High	2/2	2
Impacts on social equity and justice	Medium	1/2	4	Medium	1/1	3
Impact on trust between institutions and community	Medium	2/2	5	Medium	1/1	3
Land consumption	Low	1/1	6	Low	1/1	4

Table 6. Pairwise comparison of positions across the group rankings, supporting the derivation of the shared hierarchy under Approach 2 for the attributes related to intrinsic characteristics of the measures (Workshop 2).

ATTRIBUTE	GROUP 1			GROUP 2		
	Class	Class rank	Overall rank	Class	Class rank	Overall rank
Performance under uncertainty	High	1/1	1	High	1/1	1
Engagement of stakeholders	Medium	1/1	2	High	1/1	1
Ease of maintenance	Low	1/1	3	Low	1/1	2

As a first attempt, weights were computed using the revised Simos procedure (Figueira and Roy, 2002). In this method, a base (non-normalized) weight of 1 is assigned to the least important attribute (or set of ex-aequo attributes), and weights for subsequent ranked positions are increased by a fixed increment. When one or more blank cards are placed between two consecutive attributes, the increment is multiplied (e.g., doubled for one blank card, tripled for two) to reflect larger perceived differences in importance. However, a practical limitation emerged when some groups (especially in the first workshop) were unable to complete the within-class ordering due to time constraints, resulting in several attributes being left ex-aequo. Since the revised Simos method interprets ex-aequo positions as genuine indifference, this may collapse multiple attributes into a limited number of ranking levels and generate overly steep weight gradients (i.e., comparatively higher weights for top-ranked attributes and strongly reduced weights for lowest-ranked ones) compared to the judgement that participants intended to express during the workshop. To address this issue, an alternative calculation method (here referred to as Linear Rank-Order (LRO) weighting) was also tested to obtain a more controlled progression of weights when within-class ordering was incomplete. This variant assigns a decreasing sequence of non-normalized weights along the ranking: the most important attribute receives a maximum weight equal to the total number of positions/cards considered in each hierarchy (including blank cards), and subsequent attributes receive decreasing weights by stepwise reduction. Where a blank card is inserted, a ranking position is skipped; where attributes are ex-aequo, they receive the average weight of the occupied positions.

Overall, the testing phase produced multiple weighting configurations by combining the two aggregation approaches with alternative computational methods. In this deliverable, only the weight sets computed through the LRO method are reported (Tables 7–9). For the subsequent study application, the weights derived from the shared hierarchies under Approach 2 were adopted as the main configuration, given their stronger traceability to a consolidated preference structure, while the weights obtained under Approach 1 were retained for sensitivity analyses.

The resulting weight set and the scores assigned by the first group to the three attribute categories (Table 10) were then applied in the multi-criteria aggregation phase to compute overall performance scores for each intervention alternative, as described in the following sections.

Table 7. Weights (%) of the attributes related to risk reduction, computed using the LRO method under both aggregation approaches (Approach 1: average of group-based weights; Approach 2: weights from shared hierarchy).

<b>ATTRIBUTE</b>	<b>WEIGHTS – Approach 1 (%)</b>	<b>WEIGHTS – Approach 2 (%)</b>
<b>Affected people</b>	11.4	<b>11.8</b>
<b>Damage to residential assets</b>	9.4	<b>11.0</b>
<b>Damage to agricultural assets</b>	9.4	<b>10.3</b>
<b>Impact on atmosphere</b>	9.3	<b>9.2</b>
<b>Disruption of transport services</b>	8.2	<b>9.2</b>
<b>Impact on secondary sector</b>	7.7	<b>8.1</b>
<b>Damage to lifelines</b>	6.4	<b>7.3</b>
<b>Impact on primary sector</b>	6.7	<b>6.6</b>
<b>Impact on tertiary sector</b>	5.5	<b>5.9</b>
<b>Disruption of recreational services</b>	4.2	<b>5.1</b>
<b>Damage to industrial assets</b>	4.3	<b>3.7</b>
<b>Costs</b>	4.0	<b>3.7</b>
<b>Impact on surface hydrosphere</b>	3.7	<b>3.7</b>
<b>Indirect physical damage</b>	4.5	<b>2.2</b>
<b>Impact on cultural capital</b>	2.9	<b>1.1</b>
<b>Damage to commercial assets</b>	2.6	<b>1.1</b>

Table 8. Weights (%) of the attributes related to co-benefits and disbenefits of the measures, computed using the LRO method under both aggregation approaches (Approach 1: average of group-based weights; Approach 2: weights from shared hierarchy).

<b>ATTRIBUTE</b>	<b>WEIGHTS – Approach 1 (%)</b>	<b>WEIGHTS – Approach 2 (%)</b>
<b>Impact on community cohesion</b>	28.3	<b>28.6</b>
<b>Impact on cultural heritage</b>	22.7	<b>23.8</b>
<b>Changes in cultural landscape</b>	20.7	<b>19.0</b>
<b>Impacts on social equity and justice</b>	14	<b>14.3</b>
<b>Impact on trust between institutions and community</b>	10	<b>9.5</b>
<b>Land consumption</b>	4.3	<b>4.8</b>

Table 9. Weights (%) of the attributes related to intrinsic characteristics of the measures, computed using the LRO method under both aggregation approaches (Approach 1: average of group-based weights; Approach 2: weights from shared hierarchy).

<b>ATTRIBUTE</b>	<b>WEIGHTS – Approach 1 (%)</b>	<b>WEIGHTS – Approach 2 (%)</b>
<b>Performance under uncertainty</b>	50.0	<b>45.9</b>
<b>Engagement of stakeholders</b>	33.3	<b>37.4</b>
<b>Ease of maintenance</b>	16.7	<b>16.7</b>

Table 10. Relative importance scores assigned by the two groups of Workshop 2 to the three categories of attributes (assuming “risk modelling” score = 10 as reference).

<b>ATTRIBUTE CATEGORY</b>	<b>GROUP 1</b>	<b>GROUP 2</b>
<b>Risk modelling</b>	<b>10</b>	<b>10</b>
<b>Co-benefits and disbenefits of measures</b>	<b>6</b>	<b>6.5</b>
<b>Intrinsic characteristics of measures</b>	<b>8</b>	<b>4</b>

### 3 Proof of Concept (PoC)

This chapter outlines the case study area, describing its geographical setting, socio-economic features, and level of multi-risk exposure (Section 3.1), as well as the selected intervention options aimed at enhancing risk mitigation and promoting sustainable development (Section 3.2).

#### 3.1 Description

Lomellina is a historical region in the western part of Lombardy, located within the province of Pavia. It is bordered by the Piedmont region to the north, west and south, and its perimeter is defined by three major rivers: The Po on the south, the Ticino on the east and the Sesia on the west.

Although it has been affected by major changes in government and administration over time, Lomellina is currently divided into 57 municipalities. The main centers, in terms of accessibility, population and services, are Vigevano, Mortara, Mede, and Sannazzaro de' Burgondi.

Lomellina is divided into sub-regions with specific social, demographic, and economic characteristics. The northern and eastern municipalities are centered on Vigevano and have an industrial and tertiary sector focus, partly due to their proximity to the Milan metropolitan area. The southern and western municipalities refer to Mede and Sannazzaro de' Burgondi and are characterized by low accessibility and significant agricultural activity. The central municipalities refer to Mortara. Historically, their economy was primarily agricultural, but logistics and the third sector have increasingly become more important over the last twenty years (Caramaschi, Coppola, Vigotti, 2025).

Due to important transformations in the territory over the last 70 years – including agricultural mechanization, structural demographic and economic changes, and the construction of industrial plants at Risk of Major Accidents – Lomellina has undergone a process of peripherisation, leaving the territory 'behind' regional hierarchies. In 2021, Lomellina was designated a Regional Inner Area by the Regione Lombardia *Agenda del Controesodo* due to the territory's structural vulnerabilities. Forty-three out of fifty-seven municipalities are included in the inner area perimeter (Altre Lombardia, 2025).

From 2022, the coordination of the path towards the establishment of a territorial cohesion strategy will be handled by the Local Action Group Risorsa Lomellina. The strategy will be aimed at counteracting economic degrowth, loss of population, and lack of accessibility and essential services.

Furthermore, the Lomellina region is vulnerable to flooding, drought, and seismic activity. The flood risk is particularly evident in the south-western part of the territory, affecting the municipalities along the Po and Sesia riverbanks. Lomellina has experienced numerous catastrophic floods over the centuries. The most recent major event was the flood that occurred in 2000 and affected the municipalities located on the River Po.

In recent years, the region, which has a strong agricultural tradition centered on rice cultivation, has visibly been affected by the effects of climate change. In 2022, drought severely affected the rice fields, which require a consistent supply of water.

In relation to the research framework of Task 7.2.4, twelve municipalities were identified as Proof of Concept (PoCs). The selection of the PoC areas was guided by their differing levels of exposure to a range of risk factors. The PoC includes the municipalities of Pieve Albignola, Sannazzaro de' Burgondi, Ferrera Erbognone, Mezzana Bigli, Pieve del Cairo, Suardi, Gambarana, Frascarolo, Torre Beretti e Castellaro, Sartirana Lomellina, Breme, and Candia Lomellina.

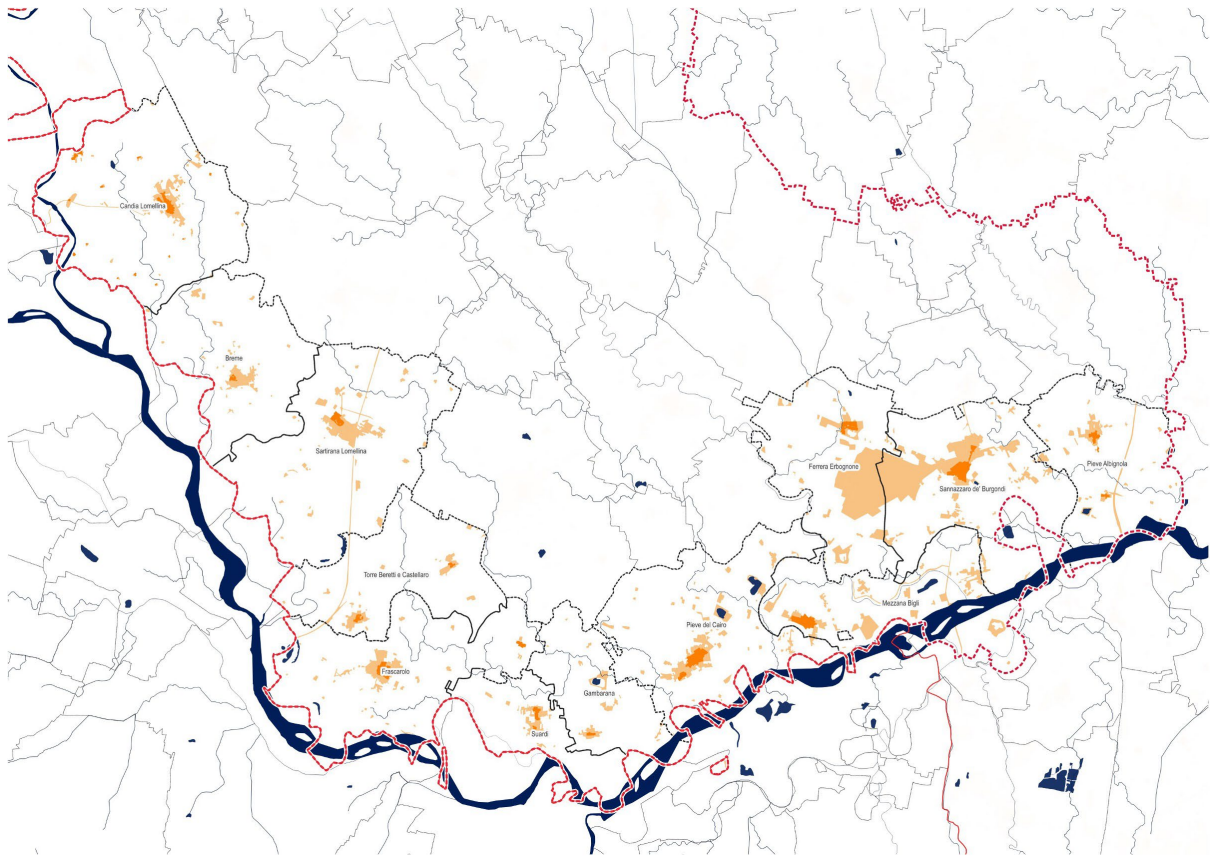


Figure 1 Localization of the 12 municipalities encompassed in the PoC.

The PoC area has a total population of 17,022 inhabitants, distributed within a highly fragmented administrative context. This institutional configuration makes it more difficult to design coordinated strategies and implement integrated policies at the territorial scale. The demographic framework is marked by a steady population decline, with consequences for the sustainability of services and the socio-economic vitality of smaller settlements. This is compounded by a significant condition of remoteness from essential services. Together, these factors reinforce processes of marginalization and highlight the urgency of structural and territorial rebalancing measures.

### 3.2 Risk reduction strategies

The Task evaluated one structural and one non-structural measure. The structural measure involves the raising of the main embankment of the Po River by one and a half meters in the municipalities of Suardi and Gambarana, which are the most exposed to flood risk. The non-structural measure analysed within the Task concerns the **relocation of residents currently exposed to flood risk** in the municipality of Suardi, Mezzana Bigli, Pieve del Cairo, and peripheral Sannazaro de' Burgondi to the historic centre of the municipality of Sannazaro de' Burgondi. The choice of Sannazaro de' Burgondi as the relocation area is based on two main considerations:

- The comparatively low exposure of the municipality to flood hazard, also attributable to the orographic configuration of the settlement, which is located on a natural terrace;
- The higher level of accessibility and the availability of essential services, including education, healthcare, and mobility infrastructure.

The measure envisages the recovery and adaptive reuse of residential buildings located within the historic centre of Sannazaro de' Burgondi. From an implementation perspective, the intervention can

be interpreted as a mutually beneficial (win-win) solution. On the one hand, relocated households would benefit from improved access to services and from housing units upgraded in compliance with current seismic safety and energy efficiency standards. On the other hand, the rehabilitation and reuse of historic buildings would contribute to reducing residential vacancy and could act as a lever for the broader regeneration of the historic centre, which is currently affected by progressive abandonment and underutilisation of its built heritage.

### **Cost estimate methodology and assumptions**

The costs of the proposed measures are described below. For the construction of the embankment, the implementation cost was estimated by multiplying the levee construction volume (322,980 m<sup>3</sup>) by a unit cost of €18.80/m<sup>3</sup> (adjusted for currency revaluation based on historical projects) and then annualizing the total over a 100-year design life. The volume was derived from a 1.5 m increase in height and a 20 m increase in width of existing levees, extending approximately 10.77 km.

For the renovation of the buildings, the cost estimate (€1,490 per m<sup>2</sup> of net usable floor area) is derived from an average of two reference price lists: the DEI price list for the Lombardy Region, updated to 2024, and the price list “*Construction Costs for New Buildings and for the Renovation and Restoration of Building Structures*” (Translation by the Authors) issued by the Order of Architects of Grosseto, also updated to 2024 (OAPPCR, 2024).

The use of an average value stems from the impossibility of directly comparing the two price lists, as they do not share identical cost items across the two regions. This approach was agreed to be the most appropriate solution, albeit approximate.

The cost per square metre was estimated on the assumption of a medium-level renovation / conservative rehabilitation intervention, typical of residential buildings located in historic centres. Such interventions generally aim to rehabilitate or restore the building fabric through: the replacement and reconstruction of horizontal elements (floors, slabs, ceilings); partial or complete refurbishment of external vertical elements (façade masonry, finishes, plasters, and painting); refurbishment of internal vertical elements (structural and non-structural), including the creation of spaces for bathrooms and kitchens; and the complete renewal of all building services and systems.

As all buildings are located within the historic centre, it was considered appropriate to apply the same average cost per m<sup>2</sup> across the three types of intervention. A more detailed estimate, disaggregated by individual cost items could be developed when required. However, for the purposes of the present assessment, the average value of €1,490/m<sup>2</sup> is considered adequate.

Interventions cost were applied homogeneously to all the buildings of the municipality. This is due to the availability and nature of data related to buildings’ construction material, structure, state of conservation and use, which can be retrieved in aggregated form from ISTAT database.

### **Selection of pilot buildings**

The selection of “pilot” buildings within the historic centre was based on the Piano delle Regole (and related regulations – Norme Tecniche di Attuazione), which forms part of the Piano di Governo del Territorio (PGT) of Sannazzaro de’ Burgondi.

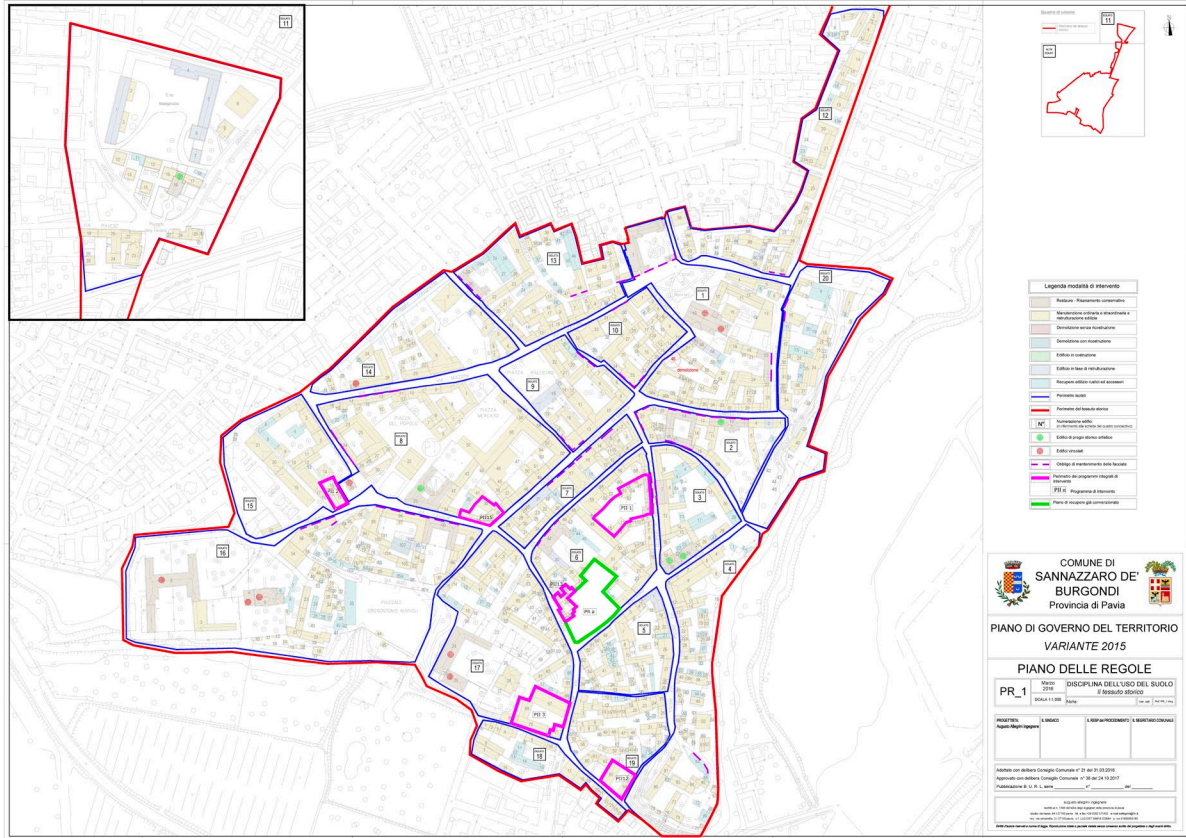


Fig. 2: Board PR\_1, Piano delle Regole: “Disciplina di intervento d’uso del suolo – Il tessuto storico”.

Once the intervention categories permitted for buildings in the historic centre had been identified, one “pilot” building was selected for each intervention type (Conservative Rehabilitation / Building Renovation / Extraordinary Maintenance) on the basis of on-site surveys. The selected buildings are currently abandoned but are in good or fair condition. Two are small in surface (approximately 80–90 m<sup>2</sup> over two storeys), while the third is significantly larger, with a surface area of approximately 450 m<sup>2</sup>. The latter likely constitutes a portion of what was originally an open “C”-shaped courtyard complex.

The following table reports the Cost estimated by building and intervention type. The data are summarised below.

Table 11. Cost estimates by building and intervention type

**Conservative rehabilitation (Restauro - Risanamento conservativo)**

*Via Garibaldi, 55 – 225 m<sup>2</sup>, two storeys above ground*

Surface (m <sup>2</sup> )	Cost €/m <sup>2</sup> / Attic €/m <sup>2</sup>	Partial total (€)	Total (€)
450	1,490	670,500	871,650
225	894	201,150	

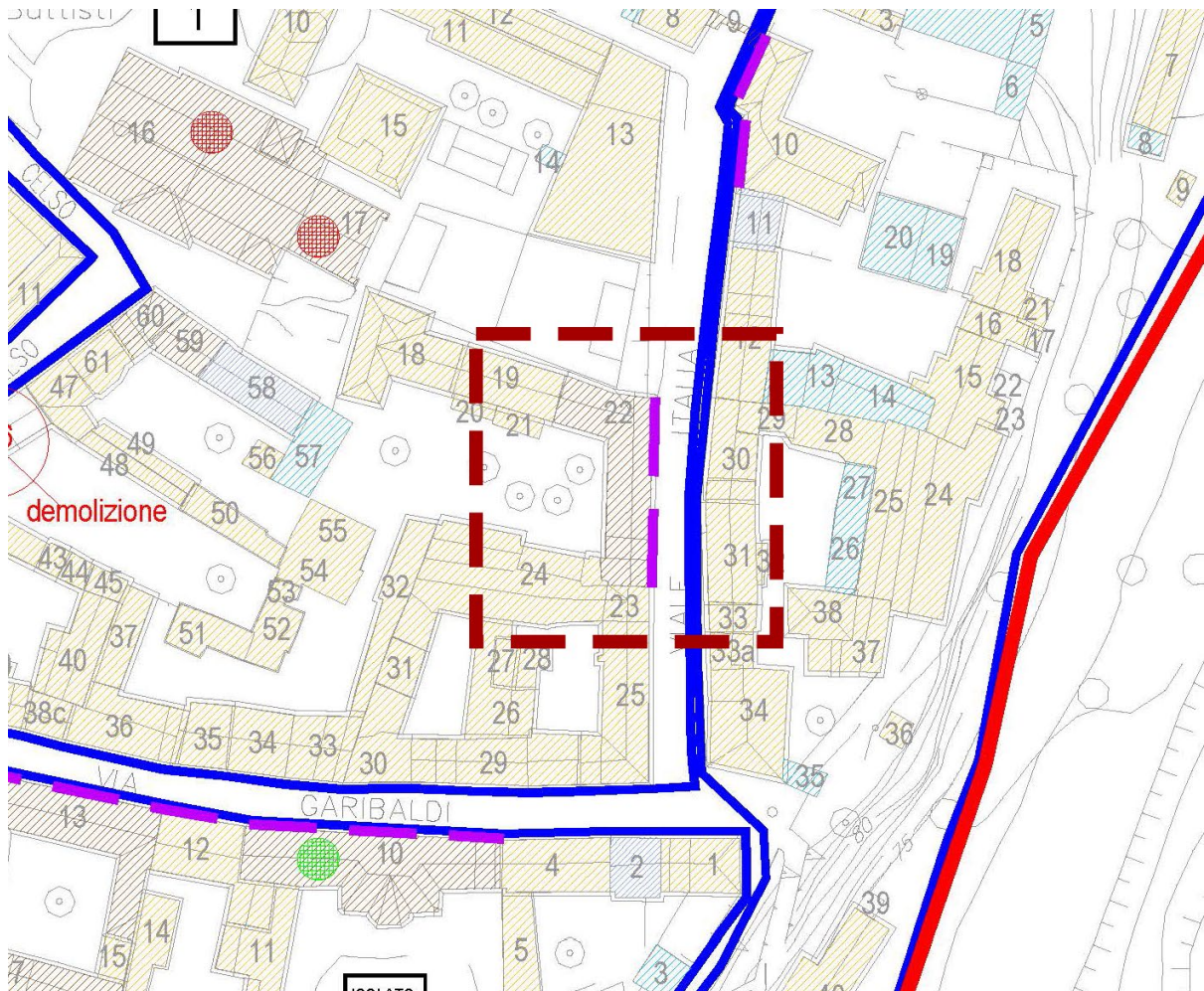


Fig. 3: Location of the building in the Piano delle Regole – Disciplina di intervento d'uso del suolo – il tessuto storico. Extract. The selected building is subjected to **Conservative rehabilitation with conservation of the façades**

### **Building renovation (Ristrutturazione edilizia)**

*Via Garibaldi, 21 – 40 m<sup>2</sup>, two storeys above ground*

Surface (m <sup>2</sup> )	Cost €/m <sup>2</sup> / Attic €/m <sup>2</sup>	Partial total (€)	Total (€)
80	1,490	119,200	154,960
40	894	35,760	

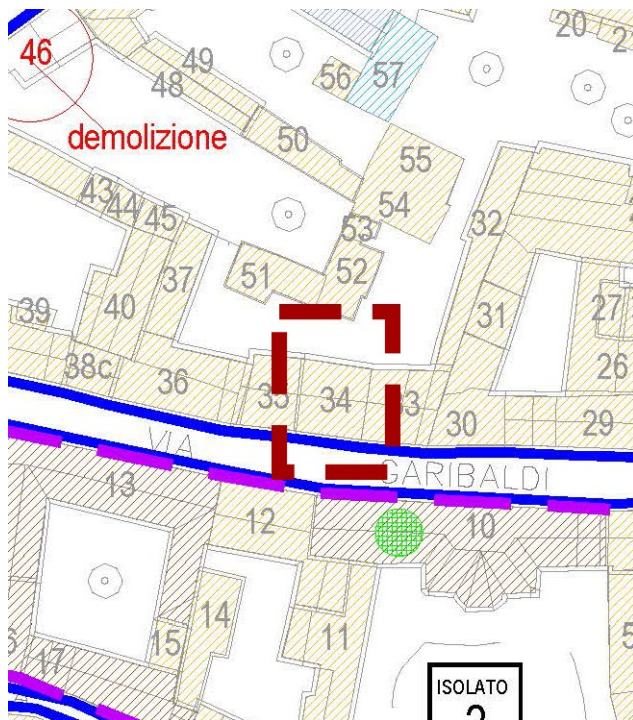


Fig. 4: Location of the building in the Piano delle Regole – Disciplina di intervento d’uso del suolo – il tessuto storico. Extract. The selected building is subject to Building Renovation.

**Extraordinary maintenance (Manutenzione Straordinaria)**

*Via Mazzini, 58 – 45 m<sup>2</sup>, two storeys above ground*

Surface (m <sup>2</sup> )	Cost €/m <sup>2</sup> / Attic €/m <sup>2</sup>	Partial total (€)	Total (€)
90	1,490	134,100	174,330
45	894	40,230	

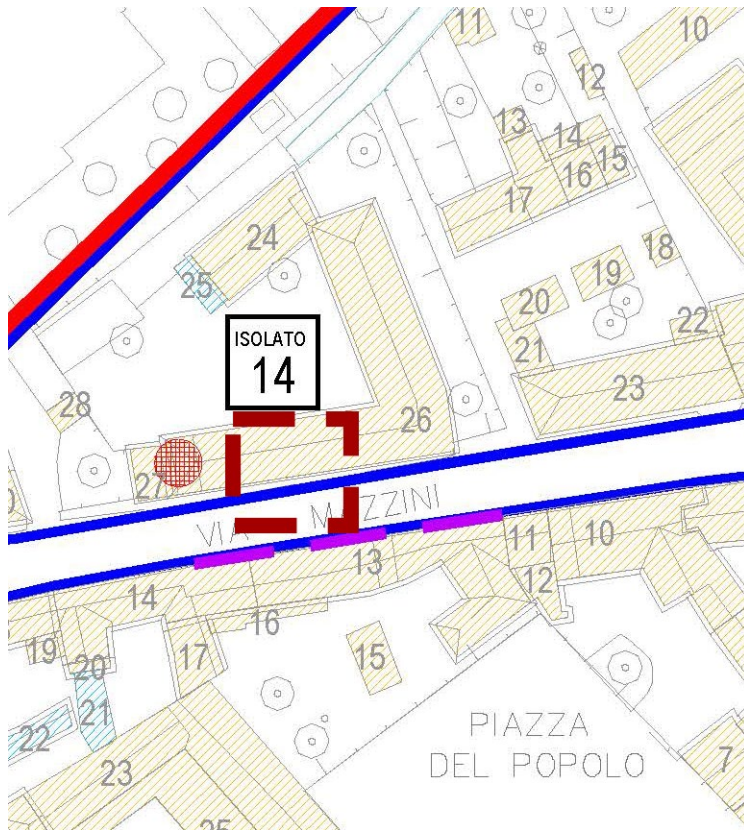


Fig. 5: Location of the building in the Piano delle Regole – Disciplina di intervento d'uso del suolo – il tessuto storico. Extract. The selected building is subject to Extraordinary maintenance.

It should be noted that the cost per square metre for attic spaces is lower, as it is calculated using a different coefficient. Finally, the building typologies and floor areas are considered adequate to accommodate the number of people to be relocated, with additional capacity potentially available for the creation of further housing units.

## 4 Results

This chapter presents the results of applying both structural and non-structural measures to the case study. The effectiveness of the interventions is evaluated in terms of their risk reduction performance (Section 4.1) and their broader sustainability contributions (Section 4.2), to ultimately produce a ranked list for supporting the prioritization of alternatives (Section 4.3).



### 4.1 Multi-risk reduction


For each dimension of the Hazards–Impacts matrix, the impact indicators are assessed and compared across the baseline scenario (Alternative 0), the structural mitigation option (Alternative 1), and the non-structural mitigation option (Alternative 2). Regarding flooding, all indicators are expressed in terms of expected annual damage (EAD), estimated for the three flood return periods (T = 50, 200, and 500 years), while assuming zero damage for T = 10 years. As concern earthquakes, all indicators are expressed in terms of expected annual damage (EAD), estimated for the return periods (T = 30, 50, 72, 101, 141, 200, 475, 1000, and 2500 years) provided by the Italian seismic hazard model MPS04 (Stucchi et al., 2011), while assuming zero damage for T = 10 years.

#### 4.1.1 Individual well-being

Table 12 summarizes the EAD for the attributes of the 'Individual well-being' dimension: direct physical damage, indirect physical damage, and affected people. Both risk mitigation strategies reduce the EAD compared with the baseline scenario. However, the magnitude of the reduction differs between the alternatives, with levee raising producing larger decreases across the indicators. The expected annual number of casualties and injuries decreases under both mitigation strategies compared with the baseline scenario. Although these values are relatively low, the reduction is greater when levee raising is implemented. Regarding indirect physical impacts, the expected annual number of people experiencing PTSD also decreases, showing the same pattern as casualties, injuries, and displaced people, since these indicators depend on the number of individuals living within the flood inundation area, which decreases under both mitigation strategies, with a larger reduction observed for levee raising. No educational institutions are located within the flood inundation area for all events; therefore, the expected number of affected students is zero across all scenarios. For employees, levee raising shows a decrease, whereas relocation remains unchanged, reflecting that the relocation strategy primarily targets the resident population.

Table 12: Assessment of multi-risk reduction for individual well-being.





Individual well-being							
	Attribute	Sub-attribute	Indicator	Scenario	Flood	Earthquake	Multi-risk
	Direct physical damage	Deaths and missing persons	Expected annual number of casualties	Baseline	< 1 person	< 1 person	< 1 person
				Levee	< 1 person	< 1 person	< 1 person
				Relocation	< 1 person	< 1 person	< 1 person
		Injuries	Expected annual number of injured people	Baseline	< 1 person	< 1 person	< 1 person
				Levee	< 1 person	< 1 person	< 1 person
				Relocation	< 1 person	< 1 person	< 1 person
	Indirect physical damage	Mental health problems	Expected annual number of people showing indications of PTSD	Baseline	5 persons	10 persons	15 persons
				Levee	3 persons	10 persons	13 persons
				Relocation	4 persons	9 persons	13 persons




	Affected people	Directly affected people	Expected annual number of people living in the affected area	Baseline	11 persons	31 persons	42 persons
				Levee	6 persons	31 persons	37 persons
				Relocation	9 persons	29 persons	38 persons
		Indirectly affected people	Expected annual number of employees and students in the affected area	Baseline	4 persons	22 persons	26 persons
				Levee	4 persons	22 persons	26 persons
				Relocation	4 persons	22 persons	26 persons
		Homeless people	Expected annual number of displaced people	Baseline	1 person	13 persons	14 persons
				Levee	< 1 person	13 persons	13 persons
				Relocation	1 person	12 persons	13 persons

#### 4.1.2 Built environment

Table 13 summarizes the EAD for the attributes of the Built environment dimension: damage to residential, commercial, industrial, agricultural, public buildings, lifelines, and cultural heritage assets. Expected annual exposure and damage generally decrease under the structural mitigation measure compared with the baseline scenario. Raising levee produces reductions across most indicators, mainly affecting residential assets and transport infrastructure. In contrast, relocation and retrofit shows no change for most indicators, with only a small reduction in residential economic damage, while railway exposure and cultural heritage damage remain unchanged in all scenarios.

Table 13: Assessment of multi-risk reduction for individual well-being.


Built environment							
	Attribute	Sub-attribute	Indicator	Scenario	Flood	Earthquake	Multi-risk
	Damage to non-productive private residential assets	Damage to residential buildings: structure and contents	Expected annual economic damage to residential buildings	Baseline	115,000.00	219,364.17	334,364.17 €
				Levee	100,000.00	219,364.17	319,364.17 €
				Relocation	100,000.00	202,684.77	302,684.77 €
	Damage to private industrial assets	Damage to industrial buildings: structure, equipment and stock	Expected annual value of exposed industrial buildings	Baseline	510,000.00	2,516,400.00	3,026,400 €
				Levee	490,000.00	2,516,400.00	3,006,400 €
				Relocation	510,000.00	2,516,400.00	3,026,400 €
	Damage to private commercial assets	Damage to commercial buildings: structure, equipment and stock	Expected annual value of exposed commercial buildings	Baseline	140,000.00	193,050.00	333,050.00 €
				Levee	130,000.00	193,050.00	323,050.00 €
				Relocation	140,000.00	193,050.00	333,050.00 €
	Damage to private agricultural assets	Damage to agricultural buildings: structure, equipment and stock	Expected annual number of exposed agricultural activities	Baseline	5 assets	3 assets	8 assets
				Levee	5 assets	3 assets	8 assets
				Relocation	5 assets	3 assets	8 assets
				Baseline	2.24 km	0	2.24 km



		Damage to agricultural infrastructure	Expected annual length of exposed irrigation network	Levee	2.15 km	0	2.15 km
				Relocation	2.24 km	0	2.24 km
	<b>Damage to public assets</b>	Damage to public buildings	Expected annual number of exposed public buildings	Baseline	< 1 asset	14 assets	14 assets
				Levee	< 1 asset	14 assets	14 assets
				Relocation	< 1 asset	14 assets	14 assets
	<b>Damage to lifelines</b>	Damage to roads and railways	Expected annual length of exposed roads and railways	Baseline	11,010,000.00	190.00	11,010,190.00 €
				Levee	10,800,000.00	190.00	10,800,190.00 €
				Relocation	11,010,000.00	190.00	11,010,190.00 €
	<b>Damage to cultural heritage</b>	Damage to cultural heritage sites	Expected annual number of exposed cultural heritage sites	Baseline	< 1 asset	3 assets	3 assets
				Levee	< 1 asset	3 assets	3 assets
				Relocation	< 1 asset	3 assets	3 assets

#### 4.1.3 Business activities

Table 14 summarizes the EAD for the attributes of the Business activities dimension: impact on primary, secondary, and tertiary sectors. Economic losses in agricultural, industrial, and commercial activities decrease under both mitigation strategies. However, raising levee consistently leads to the largest reductions, while residents' relocation produces smaller reductions or no change in most cases, as it does not reduce the flooded area. Among sectors, the industrial sector accounts for the highest expected losses, followed by the commercial sector, whereas agricultural activities experience comparatively smaller impacts.

Table 14: Assessment of multi-risk reduction for business activities.


Business activities							
	Attribute	Sub-attribute	Indicator	Scenario	Flood	Earthquake	Multi-risk
	<b>Impact on primary sector</b>	Direct and indirect economic losses incurred by agricultural activities	Expected annual impact on agricultural firms: sales, destinations of final goods, and sources of intermediate inputs	Baseline	54,109.97	7,787.00	61,896.97 €
				Levee	51,086.49	7,787.00	58,873.49 €
				Relocation	54,109.97	7,787.00	61,896.97 €
		Direct and indirect impact on the income generated by agricultural activities	Expected annual impact on Gross Domestic Product (GDP)	Baseline	9,873.01	13,798.00	23,671.01 €
				Levee	4,915.17	13,798.00	18,713.17 €
				Relocation	8,389.21	12,908.00	21,297.21 €



	<b>Impact on secondary sector</b>	Direct and indirect economic losses incurred by industrial activities	Expected annual impact on industrial firms: sales, destinations of final goods, and sources of intermediate inputs	Baseline	3,268,291.85	811,482.00	4,079,773.8 €
				Levee	3,228,243.56	811,482.00	4,039,725.5 €
				Relocation	3,268,291.85	746,225.00	4,014,516.8 €
		Direct and indirect impact on the income generated by industrial activities	Expected annual impact on Gross Domestic Product (GDP)	Baseline	422,475.09	1,189,392.00	1,611,867.1 €
				Levee	240,785.76	1,189,392.00	1,430,177.8 €
				Relocation	347,703.23	1,112,657.43	1,460,360.6 €
	<b>Impact on tertiary sector</b>	Direct and indirect economic losses incurred by commercial activities	Expected annual impact on commercial firms: sales, destinations of final goods, and sources of intermediate inputs	Baseline	582,652.26	199,283.00	781,935.26 €
				Levee	569,131.90	199,283.00	768,414.90 €
				Relocation	582,652.26	189,359.00	772,011.26 €
		Direct and indirect impact on the income generated by commercial activities	Expected annual impact on Gross Domestic Product (GDP)	Baseline	95,161.88	311,519.00	406,680.88 €
				Levee	49,911.83	311,519.00	361,430.83 €
				Relocation	82,489.41	291,421.28	373,910.69 €

#### 4.1.4 Public services

Table 15 summarizes the EAD for the attributes of the Public services dimension: disruption of public utility services and disruption of utility services. Enrolled students and available beds indicators show zero exposure across all hazard scenarios. Non-zero values occur only for the expected annual number of exposed administrative service assets, recreational and sports activity assets, and the exposed length of roads and railways. These indicators decrease only under levee raising scenario, while relocation and retrofit scenario shows no change because the relocation measure does not affect the flood inundation extent.

Table 15: Assessment of multi-risk reduction for public services.




Public services							
	Attribute	Sub-attribute	Indicator	Scenario	Flood	Earthquake	Multi-risk
	<b>Disruption of public utility services</b>	Reduced access to education	Expected annual number of exposed enrolled students	Baseline	0	3	3
				Levee	0	3	3
				Relocation	0	3	3
		Reduced access to health services	Expected annual number of exposed available beds	Baseline	0	0	0
				Levee	0	0	0
				Relocation	0	0	0



	<b>Disruption of utility services</b>	Reduced access to administrative services	Expected annual number of exposed administrative service assets	Baseline	< 1 asset	0	< 1 asset
				Levee	< 1 asset	0	< 1 asset
				Relocation	< 1 asset	0	< 1 asset
		Reduced access to recreational and sport activities	Expected annual number of exposed recreational and sport activity assets	Baseline	1 asset	0	1 asset
				Levee	< 1 asset	0	< 1 asset
				Relocation	1 asset	0	1 asset
	<b>Disruption of utility services</b>	Reduced access to transport services	Expected annual length of exposed roads and railways	Baseline	11.01 km	0.19 km	11.20 km
				Levee	10.80 km	0.19 km	10.99 km
				Relocation	11.01 km	0.19 km	11.20 km

#### 4.1.5 Environmental systems

Table 16 summarizes the EAD for the attributes of the Environmental systems dimension: impact on surface hydrosphere, impact on groundwater hydrosphere, impact on atmosphere, impact on lithosphere, and impact on biosphere. The results indicate that neither of the mitigation strategies influence the indicators at a significant level. Only a few indicators present reductions in their impacts for levee raising while most remain unchanged. For the surface and groundwater hydrosphere, levee raising presents a few reductions in the exposed protected areas, while relocation remains equal to baseline scenario. The indicators related to the quantitative status and temperature of groundwater bodies do not change across the two mitigation measures. The same pattern is observed for the impacts on atmosphere, lithosphere, and biosphere. The number of exposed polluting sources remain the same and only a small reduction occurs in levee raising for the terrestrial protected areas.

Table 16: Assessment of multi-risk reduction for environmental systems.


Environmental systems							
	Attribute	Sub-attribute	Indicator	Scenario	Flood	Earthquake	Multi-risk
	<b>Impact on surface hydrosphere</b>	Impact on surface water quality	Expected annual length of exposed surface water protected rivers	Baseline	3.35 km	-	3.35 km
				Levee	3.31 km	-	3.31 km
				Relocation	3.35 km	-	3.35 km
	<b>Impact on groundwater hydrosphere</b>	Impact on groundwater quality	Expected annual exposed groundwater protected area	Baseline	5.96 km <sup>2</sup>	-	5.96 km <sup>2</sup>
				Levee	5.90 km <sup>2</sup>	-	5.90 km <sup>2</sup>
				Relocation	5.96 km <sup>2</sup>	-	5.96 km <sup>2</sup>
		Impact on groundwater quantity	Expected annual impact on groundwater quantitative status	Baseline	Significant	-	Significant
				Levee	Significant	-	Significant
				Relocation	Significant	-	Significant
		Impact on groundwater temperature	Expected annual impact on groundwater temperature	Baseline	Significant	-	Significant
				Levee	Significant	-	Significant
				Relocation	Significant	-	Significant
	<b>Impact on atmosphere</b>	Impact on air quality	Expected annual number of exposed air	Baseline	< 1 source	-	< 1 source
				Levee	< 1 source	-	< 1 source
				Relocation	< 1 source	-	< 1 source


			polluting sources				
	<b>Impact on lithosphere</b>	Impact on soil quality	Expected annual number of exposed soil polluting sources	Baseline	< 1 source	-	< 1 source
				Levee	< 1 source	-	< 1 source
				Relocation	< 1 source	-	< 1 source
	<b>Impact on biosphere</b>	Impact on urban habitats	Expected annual exposed urban protected area	Baseline	0.001 km <sup>2</sup>	-	0.001 km <sup>2</sup>
				Levee	0.001 km <sup>2</sup>	-	0.001 km <sup>2</sup>
				Relocation	0.001 km <sup>2</sup>	-	0.001 km <sup>2</sup>
		Impact on terrestrial habitats	Expected annual exposed terrestrial protected area	Baseline	1.11 km <sup>2</sup>	-	1.11 km <sup>2</sup>
				Levee	1.10 km <sup>2</sup>	-	1.10 km <sup>2</sup>
				Relocation	1.11 km <sup>2</sup>	-	1.11 km <sup>2</sup>
		Impact on aquatic habitats	Expected annual exposed aquatic protected area	Baseline	0.05 km <sup>2</sup>	-	0.05 km <sup>2</sup>
				Levee	0.05 km <sup>2</sup>	-	0.05 km <sup>2</sup>
				Relocation	0.05 km <sup>2</sup>	-	0.05 km <sup>2</sup>

#### 4.1.6 Communities

Table 17 summarizes the EAD for the attributes of the Communities dimension: impact on cultural capital and human capital. Most indicators do not change across the scenarios, as the number of exposed cultural events and the affected educational assets remain the same. Raising levee scenario shows small reductions in the expected number of exposed cultural sites and in the exposed local skills, indicating a slight improvement compared with the baseline. On the other hand, residents' relocation reduces the expected number of buildings that become inaccessible, due to the lower exposure of buildings under this alternative.

Table 17: Assessment of multi-risk reduction for communities.

Communities							
Attribute	Sub-attribute	Indicator	Scenario	Flood	Earthquake	Multi-risk	
	<b>Impact on cultural capital</b>	Impact on community participation in cultural activities	Expected annual number of exposed cultural events that will be cancelled or relocated	Baseline	< 1 event	-	< 1 event
				Levee	< 1 event	-	< 1 event
				Relocation	< 1 event	-	< 1 event
	Impact on the transmission of cultural capital in formal education	Expected annual exposed education assets whose service will be disrupted	Baseline	0	< 1 asset	< 1 asset	
			Levee	0	< 1 asset	< 1 asset	
			Relocation	0	< 1 asset	< 1 asset	
	Impact on the conservation of cultural capital	Expected annual number of exposed cultural sites	Baseline	< 1 asset	3 assets	3 assets	
			Levee	< 1 asset	3 assets	3 assets	
			Relocation	< 1 asset	3 assets	3 assets	
	Impact on place attachment	Expected annual number of inaccessible to people buildings requiring relocation	Baseline	< 1 asset	2 assets	2 assets	
			Levee	< 1 asset	2 assets	2 assets	
			Relocation	< 1 asset	2 assets	2 assets	

 <b>Impact on local skills recovery</b>	Impact on local skills recovery	Expected annual exposed “local skills” that will be lost	Baseline	< 1 asset	-	< 1 asset
			Levee	< 1 asset	-	< 1 asset
			Relocation	< 1 asset	-	< 1 asset

## 4.2 Sustainable development

For each dimension of the Win–Win criteria, a set of indicators was evaluated and compared across the two intervention alternatives. Most indicators were analyzed qualitatively. Where direct expert appraisal was not feasible, the assessment was conducted through a structured participatory workshop involving key stakeholders from the Lomellina area.

### 4.2.1 Implementability

The implementability of the measures is summarized in Table 18. Alternative 1 involves substantially lower implementation costs (€60,720 compared to €320,000) and requires coordination among a limited number of stakeholders. In contrast, Alternative 2 demands broader and more active stakeholder engagement, while also facing stronger public opposition and greater coordination complexity. Both alternatives share similar implementation timelines and time lags, and benefit from sufficient technological and human resource capacity. However, they diverge in governance and social dimensions: Alternative 1 encounters weaker vertical conflict but significant horizontal disagreement among stakeholders.

Table 18: Implementability evaluation of the measures.

Attribute	Sub-attribute	Levee raising		Relocation and retrofit	
		Indicator	Aggregation	Indicator	Aggregation
Overall cost	Implementation cost	60,720.24 €	-	320,000.00 €	-
	Maintenance cost				
Implementation time	Implementation time	>2 & <10 (years)	Medium	>2 & <10 (years)	Medium
	Time lag	<2 (years)		<2 (years)	
Availability of technological requirements	-	Yes	-	Yes	-
Availability of human skills	-	Yes	-	Yes	-
Stakeholder involvement	-	Low	-	High	-
Social acceptability	Public acceptance	Weak	Low	Strong	Low
	Stakeholder agreement	Strong		Strong	
Transparency and communication	Communication strategies	Yes	-	Yes	-
Responsibility identification	Clarity of responsibility assignment	Yes	Yes	Yes	No
	Coordination among responsible actors	Yes		No	
Compatibility with existing plans, programs, and regulations	-	Yes, with minor consequences	-	No	-

#### 4.2.2 Reliability

Table 19 presents the reliability evaluation of intervention alternatives. While both measures exhibit substantial long-term durability (exceeding 50 years), their ease of maintenance and performance under uncertainty differs markedly. Alternative 1 is characterized by moderate maintenance but demonstrates limited adaptability and lacks reversibility. By contrast, Alternative 2 is both adaptable and reversible, although it necessitates ongoing monitoring. Neither alternative can be considered a no-regret option.

Table 19: Reliability evaluation of the measures.

Attribute	Sub-attribute	Levee raising		Relocation and retrofit	
		Indicator	Aggregation	Indicator	Aggregation
Durability	-	High	-	High	-
Ease of maintenance	-	Medium	-	Low	-
Performance under uncertainty	Adaptability	No	No	Yes	Yes
	Reversibility	No		Yes	
	No-Regret	No		No	

#### 4.2.3 Side impacts

Table 20 presents a comparison of the secondary impacts associated with the two alternatives. Alternative 1 result in increased land consumption and produces adverse social effects across several indicators, while exerting limited influence on cultural dimensions. In contrast, Alternative 2 generates positive outcomes in terms of cultural heritage protection and has the potential to enhance community cohesion and institutional trust. Environmental indicators, including air, water, and soil pollution, greenhouse gas emissions, and biodiversity, do not exhibit substantial differences between the two options. Noise impacts and risks related to illegal activities are negligible for both alternatives. However, the two measures diverge notably in their social implications: Alternative 1 raises concerns regarding social equity and justice, whereas Alternative 2 demonstrates neutral to positive social effects.

Table 20: Side impacts evaluation of the measures.

Attribute	Sub-attribute	Levee raising		Relocation and retrofit	
		Indicator	Aggregation	Indicator	Aggregation
Land consumption		Increase	-	No variance	-
Impact on noise		No	-	No	-
Impact on pollution	Impact on air quality	No variance	No variance	No variance	No variance
	Impact on water	No variance		No variance	
	Impact on soil	No variance		No variance	
Impact on GHG		No variance	-	No variance	-
Impact on biome and biodiversity		No variance	-	No variance	-
Changes in cultural landscape	Cultural landscape land cover change	No discernible	No discernible	Positive	Positive
	Continuity of traditional practices	No discernible		Positive	
	Market value of local products	No discernible		No discernible	
Impact on intangible heritage		No discernible	-	No discernible	-
Impact on physical cultural heritage		No discernible	-	Positive	-
Impact on community cohesion		Neutral	-	Positive	-

Impact on trust between institutions and community		Negative	-	Positive	-
Impact on illegal activities		Low	-	Low	-
Impacts on social equity and justice		Negative	-	Neutral	-

Overall, the findings reported in Tables 18, 19, and 20 suggest that Alternative 1 performs more favorably in terms of practical feasibility and reduced implementation costs. In contrast, Alternative 2 exhibits stronger sustainability performance, particularly with respect to flexibility, cultural benefits, and its broader social contributions.

### 4.3 Priority score

Table 21 presents a comparative assessment of the two considered risk reduction measures (levee construction and relocation) evaluated in terms of risk reduction ( $\Delta$ risk), efficiency, and weight efficiency across multiple impact categories. Overall, both measures contribute to reducing risk, but their performance differs significantly depending on the type of impact considered. The levee measure shows a consistent reduction across all impact categories, whereas relocation provides higher reductions in selected categories but has no effect on others.

In terms of affected people, relocation achieves a higher reduction (9 individuals) compared to the levee (6 individuals), resulting in a higher efficiency (150 vs 100) and weighted efficiency (20.58 vs 13.72). A similar trend is observed for impacts on mental health, where relocation again outperforms the levee. For direct damage to residential buildings, relocation is notably more effective, reducing damages by 31,706 compared to 15,000 for the levee. This is reflected in a substantially higher efficiency (211.37) and weighted efficiency (27.04), making it one of the most significant advantages of the relocation strategy.

However, the levee measure demonstrates clear advantages in several economic and infrastructure-related categories. It is the only measure that reduces direct damage to infrastructure, industrial buildings, commercial buildings, and agriculture, as well as disruptions to roads and recreational services. In these categories, relocation shows no impact ( $\Delta$ risk = 0), resulting in zero efficiency and weighted efficiency. Consequently, the levee provides a more comprehensive risk reduction across sectors.

Regarding impacts on economic sectors, the levee achieves higher reductions in the secondary and primary sectors compared to relocation, although relocation still contributes moderately in these areas. The efficiency of relocation in the secondary sector (78.82) is lower than that of the levee (100), and significantly lower in the primary sector (24.23 vs 100), which is also reflected in the weighted efficiencies.

When considering the cost of the measures, the levee is substantially less expensive (60,720) than relocation (320,000). This cost difference strongly influences the overall efficiency results, as reflected in the total efficiency values (97.9 for the levee versus 65.1 for relocation). The weighted efficiency further emphasizes this difference, with the levee achieving higher contributions across a broader range of categories.

In summary, relocation is more effective in reducing social impacts, particularly for affected people, mental health, and residential damages, while the levee provides a more balanced and cost-efficient solution with benefits across a wider set of impact categories, especially in infrastructure and economic sectors. The choice between the two measures therefore depends on whether priority is given to economic, social or environmental dimensions, according to the relative importance (weights) of criteria as derived from the preferences of stakeholders.

Table 21: Risk reduction, efficiency, and weighted efficiency of the measures.

<b>Impact Reduction</b>	<b>Risk scenario 0</b>	<b>Δrisk Levee</b>	<b>Δrisk Relocation</b>	<b>Effeciency Levee</b>	<b>Effeciency Relocation</b>	<b>Weighted efficiency Levee</b>	<b>Weighted efficiency Relocation</b>
Affected people	86	6	9	100	150	13.72	20.58
Direct damage to agriculture	2.24	0.09	0	100	0	11.98	0
Direct damage to residential buildings	334364	15000	31706	100	211.37	12.79	27.04
Roads disruption	11.02	0.21	0	100	0	10.70	0
Impact on secondary sector	5655604	180150	141991	100	78.82	9.42	7.42
Impact on primary sector	80178	3673	890	100	24.23	7.67	1.86
Direct damage to infrastructure	11010190	210000	0	100	0	8.49	0
Impact on tertiary sector	1194668	47036	30021	100	63.83	6.86	4.38
Impact on mental health	17	2	3	100	150	2.56	3.84
Direct damage to industrial buildings	3026400	20000	0	100	0	4.30	0
Disruption of recreational services	1	1	0	100	0	5.93	0
Cost of the measure		60720	320000	81.03	0	3.49	0
Direct damage to commercial buildings	333050	10000	0	100	0	1.28	0
<b>Measures efficiency</b>						<b>97.9</b>	<b>65.1</b>

Figure 6 presents the relative importance (weights) assigned to the three evaluation criteria based on stakeholder opinions, summing to 100%. Risk reduction is considered the most important single criterion, accounting for 42% of the total weight. However, the combined weight of measure characteristics (33%) and co-benefits and disbenefits (25%) exceeds that of risk reduction, totaling 58%. This pattern likely reflects the relatively low exposure to multi-risk in the area where the urgency of risk reduction is moderate. Consequently, stakeholders place relatively greater emphasis on the practical and operational aspects of measures, as well as their broader societal and environmental impacts. Overall, the results suggest that while the effectiveness of measures in reducing risk is prioritized, decision-making also strongly considers implementation-related characteristics and the co-benefits and trade-offs associated with interventions.

Figure 6: Relative importance (weight) of risk reduction, measure’s characteristics, and co-benefits and disbenefits.

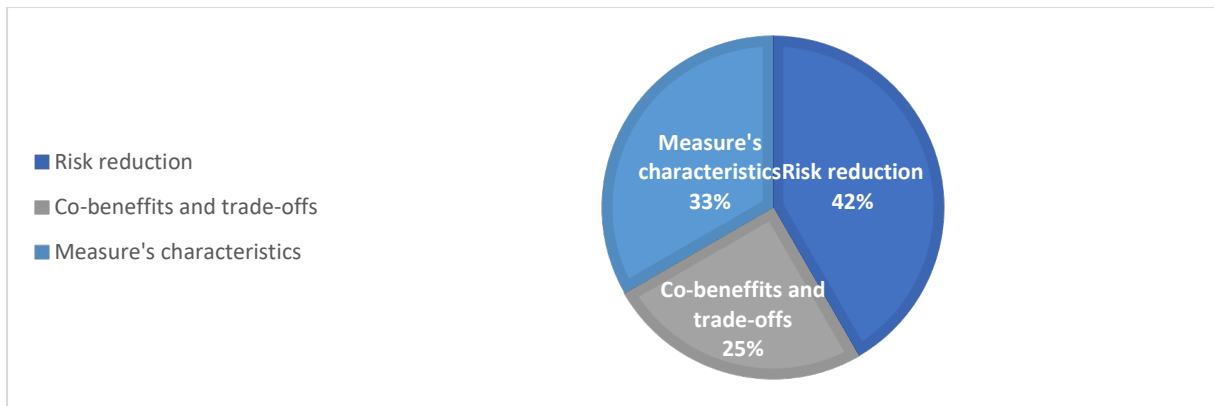
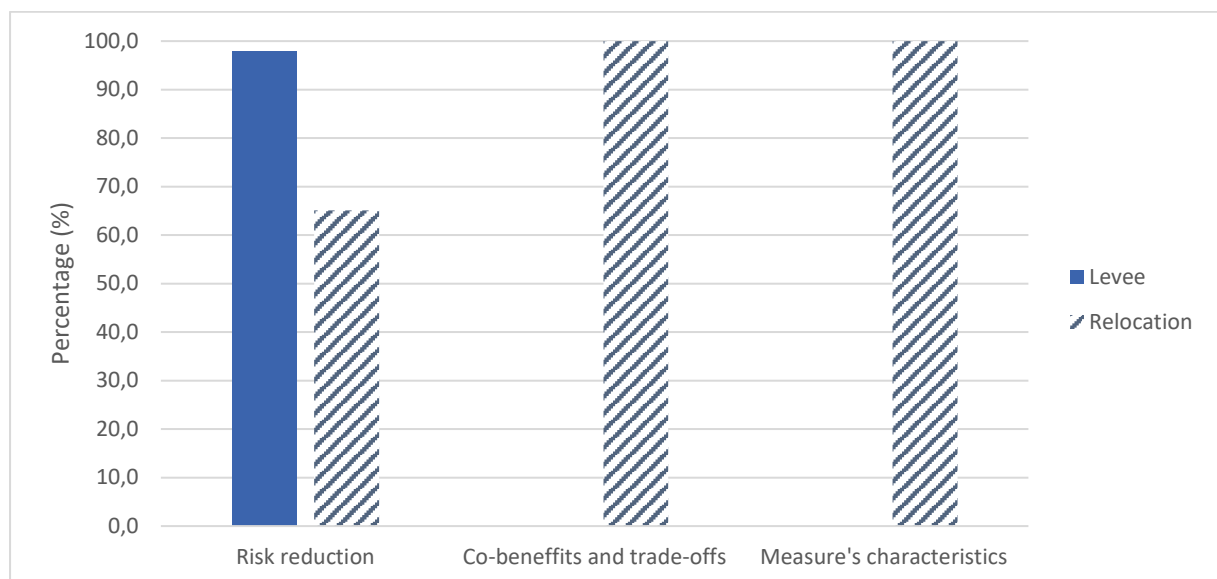


Table 22 presents the efficiency of the two measures. Levee raising achieves very high efficiency in risk reduction (97.9) but scores zero in measure characteristics and co-benefits/disbenefits, resulting in a moderate weighted efficiency of 40.8. Relocation and retrofit, although lower in risk reduction (65.1), performs perfectly in the other two criteria. Considering the weights assigned to the three criteria (42% for risk reduction, 33% for measure characteristics, and 25% for co-benefits and disbenefits) the combined performance of relocation and retrofit in the latter two categories results in a much higher weighted efficiency of 85.5. These results illustrate that, in an area with relatively low multi-risk exposure, stakeholder priorities extend beyond pure risk reduction, emphasizing practical feasibility and broader societal and environmental impacts (Figure 7).

Table 22: Efficiency of the measures.

	Levee raising	Relocation and retrofit
	97.9	65.1
	0.0	100
	0.0	100
Overall efficiency	<b>40.8</b>	<b>85.5</b>

Figure 7: Efficiency of the measures.



## 5 Concluding remarks

This Deliverable presents the application of the MCDA approach developed within the Work Package to compare two risk reduction strategies across 12 municipalities in the Lomellina area along the Po River, which is a region exposed to multiple hazards and characterized by socio-economic vulnerability. The assessment employed three complementary tools: the Hazards–Impacts matrix (Deliverable 7.2.2), the Win-Win criteria (Deliverable 7.2.3), and participatory workshops, to evaluate the strategies' effectiveness in terms of natural risk reduction and sustainable development. The strategies considered include a structural intervention (Alternative 1: levee heightening) and a non-structural measure (Alternative 2: population relocation combined with building retrofitting).

From a risk reduction standpoint, results from the Hazards–Impacts matrix indicate that Alternative 1 consistently achieves larger reductions in expected annual damage across most impact categories, including individual well-being, built environment, and business activities. This outcome is due to the direct reduction of flood extent through levee heightening, which decreases exposure for all assets. In contrast, Alternative 2 does not modify hazard conditions; its benefits are mainly limited to relocated populations, significantly improving community outcomes, while other indicators remain largely unchanged.

However, when considering the Win–Win criteria, the relocation strategy shows advantages in terms of long-term reliability and sustainability. Unlike structural measures, it avoids ongoing maintenance and uncertainties associated with levees and permanently reduces population exposure without creating residual risks behind protective structures. This comparison highlights a key insight: measures that excel in short-term risk reduction may not necessarily be the most sustainable overtime.

This conclusion is further supported when weighting attributes that compare risk reduction, co-benefits, and intervention characteristics, reflecting stakeholder preferences. Due to Lomellina's relatively low hazard exposure, local stakeholders prioritize sustainability considerations, as territorial fragility is a greater concern. Consequently, Alternative 2 is deemed the most effective and should be prioritized for investment in the area.

A key contribution of this research is moving beyond single-criterion evaluations of risk reduction measures. By integrating the Hazards–Impacts matrix with Win–Win criteria, the methodology captures both the effectiveness of interventions in reducing direct and indirect hazard impacts and their broader social, economic, and environmental implications. Stakeholders participating in workshops then evaluate the relative importance of these aspects, resulting in a comprehensive MCDA framework capable of guiding decision-making in fragile contexts, in which multiple, potentially conflicting objectives must be balanced.

Although this proof-of-concept focuses on flood and seismic risk, the methodology is designed for broader multi-hazard applications. The Hazards–Impacts matrix can be adapted to other hazards, such as landslides, droughts, and volcanic activity. Therefore, the Lomellina case study provides a transferable reference, supporting the development of consolidated guidelines for multi-risk assessment and management in diverse geographic and socio-economic settings.

## 6 References

- Altre Lombardia, Un ritratto territoriale dell'area della Lomellina: <  
[https://www.altrelombardie.polimi.it/territori/lomellina/docs/ritratto\\_territoriale/](https://www.altrelombardie.polimi.it/territori/lomellina/docs/ritratto_territoriale/)>, accessed on 10/10/25
- Caramaschi, S., Coppola, A., and Vigotti, F.: La pianura irrigua. La Lomellina tra marginalità e risorse latenti, Donzelli Editore, 2025
- Curt, C., Di Maiolo, P., Schleyer-Lindenmann, A., Tricot, A., Arnaud, A., Curt, T., Parès, N., and Taillandier, F.: Assessing the environmental and social co-benefits and disbenefits of natural risk management measures, *Heliyon*, 8(12), e12465, <https://doi.org/10.1016/j.heliyon.2022.e12465>, 2022.
- de Ruyter, M. C., de Bruijn, J. A., Englhardt, J., Daniell, J. E., de Moel, H., and Ward, P. J.: The asynergies of structural disaster risk reduction measures: Comparing floods and earthquakes, *Earth's Future*, 9, e2020EF001531, <https://doi.org/10.1029/2020EF001531>, 2021.
- FathiAzar, A., De Angeli, S., and Cattari, S.: Towards integrated multi-risk reduction strategies: A catalog of flood and earthquake risk mitigation measures at the building and neighborhood scales, *International Journal of Disaster Risk Reduction*, 113, 104884, <https://doi.org/10.1016/j.ijdrr.2024.104884>, 2024.
- Figueira, J. and Roy, B.: Determining the weights of criteria in the ELECTRE type methods with a revised Simos' procedure, *Eur J Oper Res*, 139, 317–326, [https://doi.org/10.1016/S0377-2217\(01\)00370-8](https://doi.org/10.1016/S0377-2217(01)00370-8), 2002.
- Figueira, J., Greco, S., and Ehrgott, M.: Multiple Criteria Decision Analysis: State of the Art Surveys, Springer New York, New York, NY, <https://doi.org/10.1007/b100605>, 2005.
- Hoang, L., Fenner, R. A., and Skenderian, M.: A conceptual approach for evaluating the multiple benefits of urban flood management practices, *Journal of Flood Risk Management*, 11, S943-S959, <https://doi.org/10.1111/jfr3.12267>, 2018.
- OAPPCGR, Tabella dei costi di costruzione per le nuove costruzioni e per le ristrutturazioni e restauri di manufatti edilizi, 2024
- Ruangpan, L., Vojinovic, Z., Plavšić, J., Curran, A., Rosic, N., Pudar, R., Savic, D., and Brdjanovic, D.: Economic assessment of nature-based solutions to reduce flood risk and enhance co-benefits, *J. Environ. Manag.*, 352, 119985, <https://doi.org/10.1016/j.jenvman.2023.119985>, 2024.
- Simos, J.: L'évaluation environnementale: un processus cognitif négocié, Doctoral thesis, DGF-EPFL, Lausanne, 1989.
- Simos, J.: Evaluer l'impact sur l'environnement: Une approche originale par l'analyse multicritère et la négociation, Presses Polytechniques et Universitaires Romandes, Lausanne, 1990.
- Stucchi, M., Meletti, C., Montaldo, V., Crowley, H., Calvi, G. M., and Boschi, E.: Seismic hazard assessment (2003–2009) for the Italian building code. *Bulletin of the Seismological Society of America*, 101, 1885–1911. <https://doi.org/10.1785/0120100130>, 2011.