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1. Introduction

In the context of the RETURN project, Spoke 5 TS1 "Urban and metropolitan settlements", the task 5.5.3 "The resilient-city simulation test of mitigation and adaptation scenarios", is developed in a research framework aimed at understanding and assessing the impact of mitigation and adaptation strategies in urban areas characterized by multiple and interacting risks. The results of the research activities of the task are reported in in the following document Deliverable 5.5.3 "What-if scenarios: measuring the effect of multi-risk mitigation and adaptation in case-study cities", in line with the work of previous task and work packages.

The main goal of the research activities of the task has been to develop and apply a methodological approach able to support the analysis of what-if scenarios, hypothetical constructs designed to systematically explore the potential impacts of alternative design strategies. To this end, a methodological framework is proposed – the MUHRA model – in which the what-if scenarios, articulated in both ex-ante (pre-intervention) and ex-post (post-intervention), constitute a support tool for urban planning and policy evaluation, enabling the anticipation of impacts, the optimization of decision-making processes, and the enhancement of urban resilience.

The deliverable is structured into several sections that go from the definition of the conceptual framework and the review of the state of the art on what-if scenarios, to the presentation of an integrated methodology based on indicator-driven approaches and multi-platform analytical tools. The testing of the proposed methodological approach is, furthermore, shown through a collection of empirical applications in real urban contexts, with reference to the city of Naples, serving as case studies to test and validate the MUHRA model. The tested what-if scenarios focus on the integration of adaptation, mitigation and resilience measures, as well as the development of operational tools such as catalogues of solutions and multifactorial approaches for the assessment of natural capital and its associated socio-economic benefits.

In the last section, the document outlines future developments through the proposal of a Virtual Test Bed – Returnville – conceived as an interactive environment to support the dynamic assessment of urban resilience capacity.

2. Conceptual framework

2.1. Definitions and key concepts

2.1.1. What if scenario definition. From ex-ante to ex-post scenarios

The concept of a *what-if scenario* is very broad; it generalizes all those operational contexts in which various actions are planned to strengthen the resilience of an urban settlement in the face of environmental, natural, and anthropogenic phenomena that generate risk situations for exposed assets.

In this framework, a what-if scenario identifies a set of various actions, be they intervention strategies at different scales, governance policies, population engagement, etc., aimed at reducing the impacts/risks of environmental, natural, and anthropogenic phenomena on exposed assets.

A specific what-if scenario is one in which no action is planned and the intention is to maintain the status quo. It generates an impact/risk scenario, referred to as an *ex ante scenario*, and allows the decision maker to assess the risks to the exposed assets if no action were taken on the urban settlement.

In other cases, the result of applying the actions envisaged in a what-if scenario constitutes a new impact/risk scenario, referred to as an *ex post scenario*. It provides the decision maker with a significant element for assessing the resilient effectiveness of the actions in a what-if scenario, as, when compared with the impact/risk scenario, it allows them to assess the extent to which they have been reduced.

Clearly, an ex ante scenario can further worsen the current risk scenario. For example, suppose that, using a specific model, a risk scenario for the resident population generated by the occurrence of seismic events has been generated, and the decision maker intends to assess what could happen if, within a defined time frame, preventive actions are not taken, such as seismic retrofitting of buildings. This what-if scenario will generate an ex ante scenario representing the risk scenario for the population at the end of the analyzed period. It will be worse than the initial risk scenario because inaction during the period will have led to further deterioration in the condition of the buildings, making them more vulnerable to seismic events.

2.1.2. What-if scenarios: state of art

In recent decades, climate change has caused a substantial increase in the frequency, intensity and unpredictability of extreme weather events worldwide (Hu, 2023). Between 2001 and 2023, the annual average of natural disasters stood at 380, significantly exceeding the average of 71 observed from 1900 to 1991 (Ritchie, 2023). Many of these events, such as earthquakes, volcanic eruptions, tsunamis, heavy rains, heat waves and floods, are sudden and catastrophic in nature, posing significant challenges to accurate forecasting and emergency response (Mitchell, 2006). Following these extreme weather events, multiple consequences can emerge in affected regions, including widespread disruption of social and commercial activities, fuel and energy supplies, and limited access to critical resources (Guth, 2019) (Monteleone, 2023). This, in turn, caused the deaths of 1.4 million people from 2001 to 2023, with droughts, storms and floods accounting for half of these deaths and economic losses estimated at USD 143.5 billion (CRED, 2023) (Ritchie, Natural Disasters. , 2023).

Consequences are further intensified in cascading disasters, where multiple events add up and are characterised by various critical features, such as interconnectedness, non-linear dynamics, amplification of impact, multidimensional effects, feedback loops, complexity and unpredictability, spatial and temporal spread and exacerbation of vulnerability (Berariu, 2015) (Cutter, 2018) (Dunant, 2021) (Suppasri, 2021). This results in short response times for those affected due to the abrupt and unpredictable nature of such events, amplifying the overall impact and complexity of the crisis (Pescaroli, 2018). Due to the multifaceted interactions between physical, social, economic and environmental factors, cascading disasters therefore pose significant challenges in effectively deploying response and recovery efforts, as individuals may convey various types of unwarranted or suboptimal responses in the different stages of cascading disasters, such as panicking, spreading rumours, refusing help, hoarding or selfishness, risk-taking, superstitions, looting and violence, and blaming others, driven by demands for access to critical resources (e.g. fuel, food, water) or psychological support (Mizrahi, 2020).

It is therefore understood that climate change leads us to seek adaptation and mitigation solutions to reduce the damage and costs associated with the occurrence of events, but in this framework uncertainty becomes the decisive factor for adaptation. In the framework outlined, what-if scenario planning supports urban disaster resilience by helping to make immediate decisions, with targeted interventions to mitigate socio-economic vulnerabilities.

The development of what-if scenarios is linked to the complexity of the urban system characterised by a concentration of human and infrastructural capital linked to further interconnected aspects such as social, economic and environmental aspects (Masson, 2014). For example, people are led to choose their housing in response to certain parameters such as accessibility to services, distance from their workplace or their financial resources (Hamilton, 2010) (Brasington, 2005); the need to feed the population leads to a reshaping of agricultural land around the city itself but also beyond its boundaries with a long-term impact on the global environment (Billen, 2012). Hence, in line with (Masson, 2014) , for urban settlements, such complex and connected iterations require adaptation strategies that are able to hold the interacting processes together both by adopting a systemic, numerical and multidisciplinary approach to respond to the European planning objective of understanding how risks and their management will reduce spatial vulnerability versus costs (Farinós-Dasí, 2024).

What is a what-if scenario?

Scenarios are based on the assumption that despite the unpredictability linked to climate change, some events are predetermined and, although no scenario can give a precise description of the occurrence of future events, they can help the network of academia, organisations and government leaders in making immediate decisions in the face of a nefarious event by overcoming those limits linked to uncertainty and that "tunnel vision" (Schoemaker, (1995)) linked to everyone's cognitive background in order to work in networking (Roubelat, (2000)).

For the understanding of the environmental context in which one operates, methods and strategies have been developed that, however, seem to be insufficient to describe its complexity and uncertainty. Against this backdrop, traditional approaches, while offering anticipatory solutions to deal with these changes, often return punctual and rapid solutions that are unable to inform all stakeholders such as organisational leaders (Eisenhardt, (1999). Scenario planning, established as a method of inquiry more than half a century ago, has become the backbone of future science and forecasting.

Scenario planning was widely used in military planning after World War II and, thanks to Kahn, the "father" of modern scenario planning, found further scope in political forecasting from social forecasting. In the 1970s, the scenario approach was introduced in industry by the Royal Dutch/Shell Group by Wack P. and, thanks to Godet and the La Prospective school , soon spread to the old continent as well (Van der Heijden K. , (2005)). Since Khakee (Khakee, (1991)), the definition of scenario has been questioned by framing it as deficient and, consequently, as an obstacle to technological progress. The fact is that the term scenario is often juxtaposed with other terms at the risk of eluding the optimal and shared meaning.

A confusion between method and theory emerges in the scientific literature. The theory employed in scenario planning is described by Chermack T. J. (Chermack T. J., (2002)) as 'dismal' as opposed to an analytical emphasis on practical application. The consequence, in scientific teminology, is the assertion that the field is devoid of continuous quality theory the result of disappointing theory (Chermack T. J., (2002)) and methodological chaos (Martelli, (2001).

Scenarios, take on a crucial role with respect to the epistemological and ontological foundations of future studies (Staley, (2017)), risking pulling the scientific community away from the tunnel that connects future thinking to the present in a time yet to come (Rowland, (2015)). In this time frame, it is still possible to operate the science of prediction, thanks to simulations. The concept of Future (used in the singular) is reflected in the multiple definitions of strategic planning through the various what 'if scenario processes that contribute to urban resilience for environmental sustainability.

Methodology aimed at the terminological definition of the what-if scenario of method and process

In order to link the concept of the what-if scenario to other domains besides urban planning, it is useful to conduct a bibliometric analysis (Crane, 1972) to define the state of the art with respect to scientific research on urban scenarios and to explore how transfer from other scientific domains can contribute to urban and environmental resilience related to ongoing climate change.

In the Phase I of the research work, an articulated workflow was carried out (Börner, 2003)(Zupic, 2015):

- Study design;
- Data collection;
- Data analysis;
- Data visualisation;
- Interpretation.

In the Phase II, the contributions closest to the AEC sectors in terms of the issues addressed were highlighted. However, while this phase brings us closer to the sector, it also runs the risk of highlighting that gap that is linked to the use of scenarios, i.e. there is a risk of further distancing the AEC sector from a multidisciplinary approach aligned with quantum science.

In the Phase III of the research work, the literature review follows a structured method choice to extract specific information structured according to the table 1.

Table 1. Table for the cataloguing of scientific evidence for the terminological definition of the what if scenario

SCIENTIFIC ARTICLE	
AUTHORS	
RESEARCH OBJECTIVES	
WHAT RISK ARE TO BE MITIGATED?	
SCENARIO ANTE	
METRICS	

SCENARIO POST
METRICS
TOOLS

The literature review is structured to answer the following research questions:

- Are what-if scenarios an aid in combating climate change for urban systems?
- Identify climate proof design solutions in response to climate change.
- Identify possible "what if" scenarios for urban systems?
- Do what if scenarios help develop metrics for assessing climate change risks in urban systems?
- Do what if scenarios help develop metrics for vulnerability and exposure in response to climate change risks in urban systems?
- How do what if scenarios relate to addressing climate change?
- What is the importance of using tools such as GIS in combating climate change for urban settlements?

Table 1 shows the structure of the bibliometric review, with respect to the objective of defining the what if scenario in response to the seven research questions above. The questions were directed to the Scopus search engine (http://www.scopus.com), restricting the field of research to engineering and multidisciplinarity[1], in the period between 2019-2025. The result is a bibliographic database consisting of 38 scientific contributions (tab. 2).

Table 2. Study Design

	FILTERS **Range: 2019-2025** **Filter by subject area: Engineering-Multidisciplinary** **Query: Article-Abstract-Keywords**	**SCOPUS**	
		N°	Database
I.	(climate AND change) AND (urban AND system) AND (scenario AND what AND if)	12	1
II.	(urban AND system) AND (climate AND proof AND solution AND design)	5	2
III.	(scenario* AND what-if) AND (urban AND system) AND (climate AND models)	1	3
IV.	(scenario* AND what-if) AND (urban AND system) AND (risk AND (assessment OR factor*))	2	4
V.	(scenario* AND what-if) AND (urban AND system) AND (risk AND (vulnerability OR exposure))	2	5
VI.	(what-if AND scenario*) AND (climate AND change)	21	6
VII.	((urban OR metropolitan) AND settlement) AND (climate AND change) AND (GIS)	10	7
		Total 38	

Table 3. Bibliographic Archive

TITLE	REFERENCE	DOI
IoT-Based Horticulture Monitoring System	(Rabka, (2022))	10.1007/978-981-16-6369-7_68
Synergetic Planning and Designing with Urban FEW-Flows: Lessons from Rotterdam	(Tillie, (2021))	10.1007/978-3-030-61977-0_7
How to Stay Cool Without Fossil Fuel. A Passive Low-Tech Cooler for Extreme Climates	(Dabaieh, (2023, July))	10.1007/978-3-031-36320-7_46
Sustainable urban landscapes: a computation framework for enhancing sustainability in early-stage design	(Yoffe, (2024))	10.1108/ARCH-06-2023-0152
Architectural Photovoltaic Applications: Lessons Learnt and Perceptions from Architects	(Haghighi, (2021))	10.3390/buildings11020062
Planning the resilient city: Investigations into using "causal loop diagram" in combination with "UNISDR scorecard" for making cities more resilient	(Dianat, (2021).)	10.1016/j.ijdrr.2021.102561

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[1] Since the ultimate goal is to give a definition to the what-if scenario for the city understood not as an urban system but as an urban settlement, "multidisciplinarity" was considered in the sense of the transfer of results from other scientific fields to those concepts typically related to urban planning.

Assessing community resilience, housing recovery and impact of mitigation strategies at the urban scale: a case study after the 2012 Northern Italy Earthquake	(Basaglia, (2020))	10.1007/s10518-020-00919-8
Participatory Sensing and Digital Twin City: Updating Virtual City Models for Enhanced Risk-Informed Decision-Making	(Ham, (2020))	10.1061/(ASCE)ME.1943-5479.0000748
A Digital Twin for Climate Extremes Using Artificial Intelligence	(Pagé, (2023, October))	10.1109/e-Science58273.2023.10254928
HAIVA: hybrid ai-assisted visual analysis framework to study the effects of cloud properties on climate patterns	(Hazarika, (2023, October))	10.48550/arXiv.2305.07859
Small-Scale Irrigation: Improving Food Security under Changing Climate and Water Resource Conditions in Ethiopia	(Zhang, (2024))	10.1061/JWRMD5.WRENG-6190
Bayesian Network Analysis for Shoreline Dynamics, Coastal Water Quality, and Their Related Risks in the Venice Littoral Zone, Italy	(Pham, (2024))	10.3390/jmse12010139
A digital twin of multiple energy hub systems with peer-to-peer energy sharing	(Li, (2025))	10.1016/j.apenergy.2024.124908
Failure Conditions Assessment of Complex Water Systems Using Fuzzy Logic	(Milašinović, (2023))	10.1007/s11269-022-03420-w
A quantitative comparison on the use of thermal insulation materials in three European countries through the TEnSE approach: Challenges and opportunities	(Frasca, (2023))	10.1016/j.buildenv.2023.110973
What If Country Commitments for CO2 Removal Were Based on Responsibility for Historical Emissions?	(Torvanger, (2023))	10.3390/en16114350
Efficacy of Nature-based Solutions for coastal protection under a changing climate: A modelling approach	(Marino, (2025))	10.1016/j.coastaleng.2025.104700
i-RAT: A discussion support system to rapidly assess economic and environmental impacts of different sugarcane irrigation practices	(Collins, (2023))	10.1016/j.compag.2023.108380
A Possible Model of Resilient and Environment-Friendly Transport: Assessment of Users' Propensity Towards Demand Responsive Transit (DRT) Service	(Sturiale, (2024, May))	10.1007/978-3-031-74704-5_36
Computing Vegetation Indices from the Satellite Images Using GRASS GIS Scripts for Monitoring Mangrove Forests in the Coastal Landscapes of Niger Delta, Nigeria	(Lemenkova, (2023))	10.3390/jmse11040871
Assessing seasonal dynamics of land surface temperature (LST) and land use land cover (LULC) in Bhairab, Kishoreganj, Bangladesh: A geospatial analysis from 2008 to 2023	(Saha, (2024))	10.1016/j.cscee.2023.100560
From Geodesign to Geoart: Maximising Research Impact in a Georesilience Framework	(Tara, (2024))	10.14627/537752065
City-scale model to assess rooftops performance on air pollution mitigation; validation for Tehran	(Motlagh, (2023))	10.1016/j.buildenv.2023.110746
Methodology for the Assessment of Multi-Hazard Risk in Urban Homogenous Zones	(Mladineo, (2022))	10.3390/app122412843
Urban Ecosystem Services: Land Cover and Potential of Urban Soils	(Falasca, (2023, September))	10.1007/978-3-031-54096-7_19
Examining the suitability of the local climate zones (LCZ) framework in informal urban settlements: Insights from Kabul, Afghanistan	(Akbari, (2024))	10.1016/j.scs.2024.105797
Land Subsidence and Groundwater Storage Assessment Using ICOPS, GRACE, and Susceptibility Mapping in Pekalongan, Indonesia	(Hakim, (2023))	10.1109/TGRS.2023.3324043
Land use and urban sustainability assessment: a 3D-GIS application to a case study in Gozo	(Morosini, (2019))	10.1186/s40410-019-0106-z
Integrating future trends and uncertainties in urban mobility design via data-driven personas and scenarios	(Gall, (2023))	10.1186/s12544-023-00622-0
Operational and emerging capabilities for surface water flood forecasting	(Speight, (2021))	10.1002/wat2.1517
Course change: Navigating urban passenger transport toward sustainability through modal shift	(Müller, (2022))	10.1080/15568318.2021.1919796
The benefits of nature-based systems in a changing and uncertain world	(Ashley, (2022, July))	10.1680/jensu.21.00102
A framework for assessing flood risk responses of a densely urbanized watershed, to support urban planning decisions	(de Oliveira, (2023))	10.1080/23789689.2023.2175139

On the Need for an Integrated Large-Scale Methodology of Coastal Management: A Methodological Proposal	(Armenio, (2020))	10.3390/JMSE8060385
Lifestyle changes for climate mitigation in cities and their relationship to urban health and well-being: A literature review	(Sirin, (2024))	10.1016/j.scs.2024.106069
The Integrated Modification Methodology	(Tadi, (2020))	10.1007/978-3-030-44352-8_2
An Integrated Framework for Incorporating Climate Risk into Urban Land-Use Change Modeling	(Aydin, (2022))	10.3850/978-981-18-5183-4_R25-01-258-cd
Development of an urban household food-energy-water policy nexus dynamic simulator	(Xue, (2021))	10.1016/j.jclepro.2021.129521

Data analysis aimed at defining what scenarios. Phase I: bibliometric review

Most of the research papers were published in the scientific journal Jounal Of Marine Science And Engineering ((Pham et al., 2024),(Lemenkova & Debeir, 2023), (Armenio & Mossa, 2020)), followed by A+Be Architecture And The Built Enviroment ((Dianat et al, 2021), (Aydin et al., 2022)), Building And Environment ((Frasca et al., 2023), (Banirazi Motlagh et al., 2023)), Lecture Notes In Network And Systems ((Tillie & Roggema, 2021), (Sturiale, 2024)), Sustainable City And Society ((Akbari & Sharifi, 2024), (Sirin et al., 2025)). However, the highest number of citations was obtained by publishing with (Ham & Kim, 2020) in Journal Of Management In Enginereeng.

However, the highest number of citations was obtained by publishing with (Ham & Kim, 2020) in Journal Of Management In Enginereeng. Moreover, among the most active countries, Italy stands out as contributing in no less than 37 scientific articles of those submitted for bibliographic review (fig. 1).

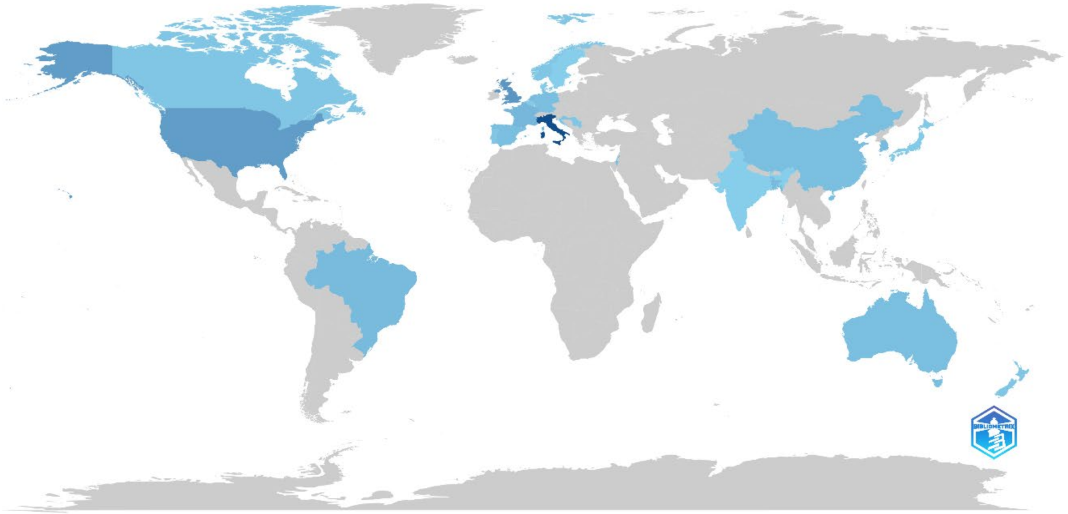

Figure 1. Country Scientific Production (Images are the result of the data analysis conducted on R-Studio to A. Rocco versus scientific evidence and cannot be substituted)

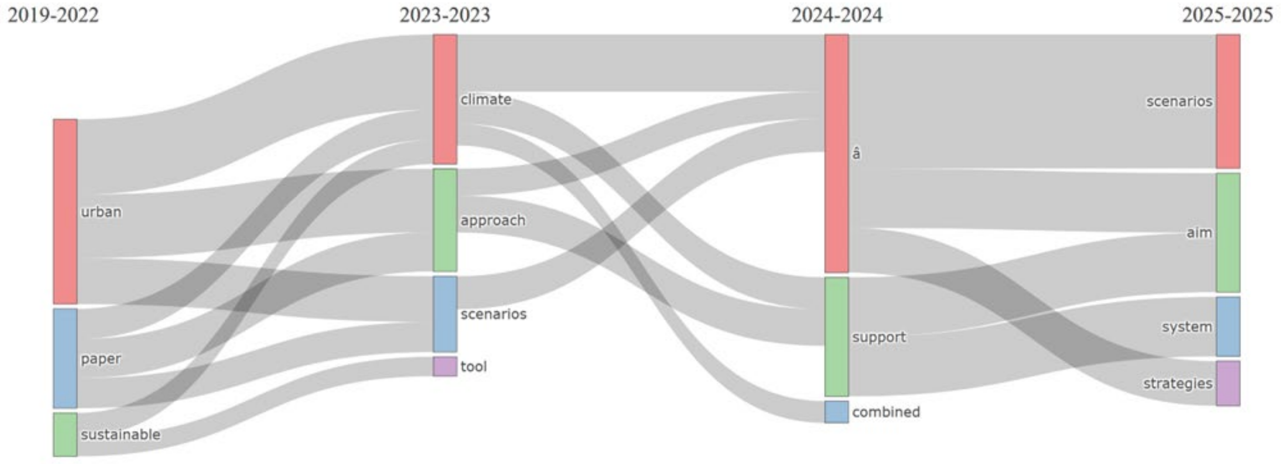

Figure 2. Thematic evolution (Images are the result of the data analysis conducted on R-Studio to A. Rocco versus scientific evidence and cannot be substituted)

The most cited paper with 135 citations is “Participatory Sensing and Digital Twin City: Updating Virtual City Models for Enhanced Risk-Informed Decision-Making” (Ham & Kim, 2020). The objective is to provide end users with an interactive on-demand Digital Twin (DT) for change related to generic extreme events in the future climate to assess impacts in different applications. The DT will enable end-users to run what-if scenarios on demand to better assess the impact of climate change on different real-world applications in specific regions, to better adapt and prepare society by exploiting new technologies such as AI, NN, ML.

Interestingly, among the most frequently cited words are “climate change”, followed by “decision making”, “carbon dioxide”, “risk assessment”. building' and “climate model”, followed by terms such as “irrigation”, “land use” and “budget control”. This result suggests that the first step in mitigating the effects of climate change risks is to model scenarios that first consider building-related metrics such as footprint, exposure and height. Interestingly, among the most frequently cited words are “climate change”, followed by “decision making”, “carbon dioxide”, “risk assessment”. building' and “climate model”, followed by terms such as “irrigation”, “land use” and “budget control”.

From the data analysis with respect to the thematic evolution of the abstracts (fig. 2), it is evident that the urban dynamics of the city, began to interface with climate scenarios from 2023, colliding in 2024 with ‘the case is grim’ (Chermack T. J., (2002)) leading to today's need to define the objectives and strategies of what if scenarios for urban settlement systems. Compared to the past decade, today, digital tools such as Digital Twins, make it easier to manage the scenarios operated against the different layers of Ratti's Sensible City to return the resilient scenario from the present-future tunnel.

Data analysis aimed at defining what scenarios. Phase II: relevance to the topics related to the AEC sector (Architecture, Engineering, Construction)

If we analyse how much scientific evidence directly interfaces with the disciplinary fields of architecture and engineering, it emerges that only 16 articles were produced in the departments of Engineering and Architecture. It is considered, however, to point out a specific relevance of topics to the individual academic and production fields, but in line with quantum science, in order to operate multidisciplinary what-if scenarios, it is essential to also evaluate the methodologies and metrics that emerged from the other 22 contributions (fig. 3).

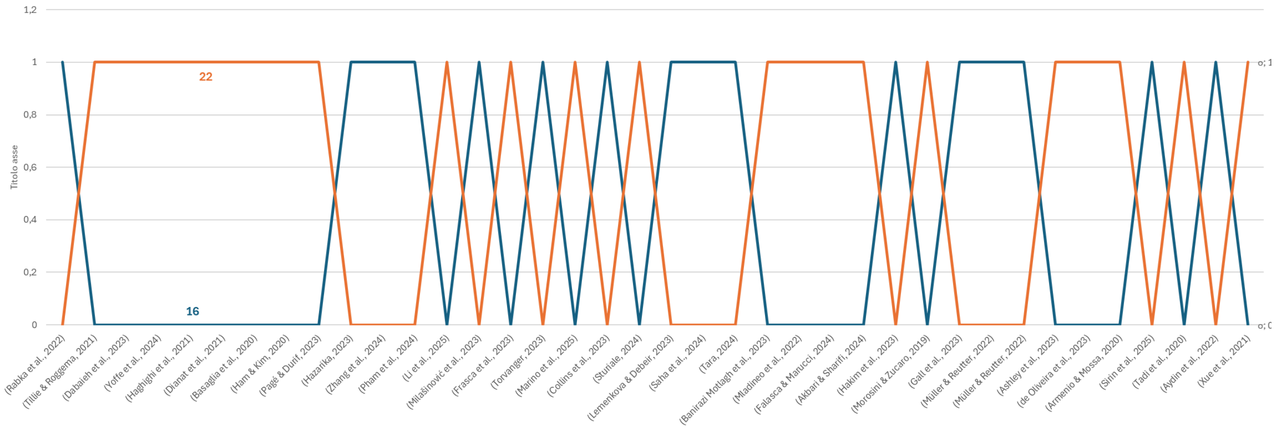

Figure 3. Relevance of the scientific contributions of the literature review to the AEC sector (Images are result of the data analysis conducted on R-Studio to A. Rocco versus scientific evidence and cannot be substituted)

Data analysis aimed at defining what scenarios. Phase III: literature review according to Table 1

Discussion of results

A further step is to define the metrics of pre- and post-event analyses aimed at reducing the effects of disasters on urban settlements by increasing their "resilience" to withstand the impact of unpredictable stresses and shocks. For example, Dianat et al (2021) projected "what if" scenarios by enabling visual outputs to visualise how certain changes made in one indicator (e.g. imposing a policy or plan) can bring about changes (positive and negative) in other environmental contexts as shown in their causal loop diagram (CLD) developed in combination with the UNISDR Scorecard quantitative resilience measurement tool for disaster risk reduction, all resilience indicators within cities are highly interconnected and building resilience requires multi-organizational efforts.

This makes it possible to infer that Digital Twin tools need to process what if scenarios in real time by drawing on systems science. Therefore, in order to verify the climate change metrics against the UNISDR Scorecard input output indicators, Table 3 shows how the two languages link for the drafting of impact chains.

Table 4. Climate Indicators and Links to the Disaster Resilience Scorecard

CLIMATE INDICATOR	LINK TO ESSENTIALS	LINK TO ADVANCED INDICATORS (117)
Urban Heat Island (UHI)	1, 4, 5, 6, 9, 10	2.1.1, 4.1.1, 5.1.1, 6.1.2, 9.2.1
Urban Heat Mitigation (HIM)	1, 4, 6, 10	4.1.1, 4.3.2, 6.1.2, 9.2.1
Biomass Density Index (BDI)	4, 5, 6, 9	4.1.1, 4.3.1, 5.1.1
Precipitation Retention Volume (RV)	5, 6, 8	5.1.1, 6.1.2
Green Cover Index (GCI)	4, 5, 6, 9	4.1.1, 4.3.2, 9.2.1
Impervious Surface Index (ISI)	4, 5, 6, 7	4.1.1, 6.1.2, 9.2.1
Tree Resilience Index (TRI)	5, 6, 7, 9	5.1.1, 8.1.1, 9.2.1
Thermal Health Index (THI)	8, 7, 9	8.1.1, 9.2.1
Nature-Based Solutions (NBS)	5, 6, 7	5.1.1, 6.1.2

However, the first step in operating what-if scenarios lies in the loyalty of the individual scriptwriter to his or her scientific community as each modelling process follows standards (UNI, EN) aimed at cost-benefit analysis (CBA). The main findings show that in fact, while the cost-benefit analysis of adaptation measures for urban settlements has to cope with numerous long-term socio-economic and climate change uncertainties with gaps and inconsistencies in planning future what-if scenarios, the extension of cost-benefit analysis to take into account the main uncertainties that characterize any decision for mitigation, economic development, health and welfare (Markanday, (2019)).

Conclusions

We started from the origins of an iconic statement in the science of futures and forecasting: the field suffers from confusion regarding the definition of the what if scenario, a concept that guides all evaluations. The literature shows that scenarios are defined by a temporal property rooted in the future and refer to external forces in a given environmental context of urban settlements. Furthermore, scenarios manifest themselves in the form of ensembles inhabited, in turn, by other scenarios, produced to coexist as significantly different alternatives to each other. Indeed, we could say that there is a scenario definition for every scenario planner in the field but, in practice, the field looks bleak where a single possible and resilient scenario cannot be returned to cross the tunnel to environmental sustainability in the near future. Hence, definitions may differ, but they must not confuse the field's scriptwriters by making assessments not aimed at univocity but adhering to reference standards (UNI, EN). In practice, these differences flatten out if the process methods in any scientific knowledge are aimed at Life Cycle Thinking and cost-benefit analysis (CBA). In fact, from CBA it is possible to extrapolate the input-output metrics of each process to the theoretical-methodical-practical scenario-what-if definition. In this way, the issues addressed in the climate change perspective can also be reflected in the next step related to Futures and Foresight Science.

2.1.3. Adaptation, mitigation, resilience capacity

Cities, as complex socio-ecological systems integrating economy, culture, and other elements, have become internationally recognized high-risk areas for major disasters, continually exposed to various external shocks and disturbances during the urbanization process (Hu et al., 2024).

In this framework, the concepts of adaptation, mitigation and resilience capacity have become central to urban governance as cities move from reactive response to proactive risk management.

Adaptation can be defined as the process of adjustment to actual or expected hazards and their impacts. In human and urban environments, it aims to moderate or avoid harm while exploiting beneficial opportunities. On the other hand, mitigation – while often used in the context of reducing greenhouse gas emissions to slow climate change – in a multi-hazard context refers to measures taken to reduce the severity or impact of disasters. Adaptation and mitigation measures work in synergy with resilience.

Resilience capacity in urban settlements refers to the capacity of urban systems to respond, recover, adapt, and transform in the face of external shocks. It is composed of three interconnected capacities: recovery capacity (the ability to rapidly restore fundamental functions after a shock, ensuring essential operations are not persistently affected), adaptive capacity (the adjustment and optimization of systems during the recovery process to better cope with future, similar shocks, this involves medium-to-long-term strategic adjustments in infrastructure and resource allocation), transform capacity (the ability to make fundamental changes when faced with irreversible shocks, this might include relocating entire urban functions or replanning coastal areas to ensure long-term sustainability).

These three strategies do not operate in isolation but through feedback loops and synergistic effects. In fact, successful adaptation and mitigation measures enhance overall resilience toward a multi-hazard risk coupling approach. For example, mitigation measures (such as energy-efficient buildings, compact urban forms, or low-carbon transport) simultaneously reduce emissions, lower exposure to climate hazards, and strengthen the adaptive capacity of infrastructure and communities. In the same way, adaptation actions (such as green–blue infrastructure, flood-resilient design, or heat-mitigating surfaces) also contribute to long-term resilience and, in many cases, co-benefits that reduce future mitigation burdens (Yan et al., 2026). Moreover, a multi-risk approach that explicitly considers interdependencies between hazards, exposures, and social vulnerabilities strengthens resilience governance, enabling integrated planning in which adaptation, mitigation, and risk-reduction strategies are co-designed with stakeholders, iteratively tested, and adapted over time (Komendantova et al., 2016).

3. The proposed methodology

3.1. Indicator approach to measure the effects of adaptive and mitigation capacities in single/integrated risk scenarios

Thematic framework

In the context of multi-risk scenarios, urban settlements represent a complex system with specific characteristics of exposure and vulnerability, which are dynamic and variable over time (Figueiredo et al., 2018). The coexistence and interaction of different hazards – climatic, environmental and socio-economic – generate cumulative and sometimes synergistic effects that amplify risk conditions, rendering sectoral and fragmented approaches to their management inadequate. It is therefore necessary to move towards integrated readings capable of capturing the interactions between environmental, physical, social and economic factors, through the development of operational tools capable of systematically reading urban systems with respect to complex and interdependent risk scenarios (Pescaroli & Alexander, 2015; Aven, 2016), in which different types of risk act simultaneously or in a chain reaction, amplifying conditions of vulnerability.

To this end, adaptation and mitigation measures are complementary and interdependent strategies. Adaptation is aimed at reducing the vulnerability of exposed elements through the implementation of strategies, actions and technical-design solutions that aim to improve the capacity to respond to and recover from damage resulting from extreme events linked to one or more hazards. Complementarily, mitigation acts primarily on the causes of the phenomena through a set of actions aimed at reducing the probability of extreme events occurring, thereby reducing the risk without eliminating it completely (Millar et al., 2012). The literature highlights how the integration of adaptation and mitigation maximises co-benefits and reduces potential trade-offs, especially in high-density and vulnerable urban contexts (IPCC, 2022).

The ability of an urban or building system to respond effectively to one or more risks depends on the combination of these two dimensions, whose positive effects are amplified when considered in synergy rather than separately (Klein et al. 2007; Landauer et al., 2015). However, this capacity is not directly observable, and measuring it is a complex but highly important challenge in order to govern and guide the transformation process (Feldmeyer et al., 2019) and is of strategic value as it allows the effectiveness of actions to be verified and transforms adaptation and mitigation into processes that can be objectively monitored over time, increasing the transparency of urban transformation processes (Biesbroek et al., 2010).

In urban areas characterised by the convergence of multiple risk factors – climatic, environmental and/or social – it is therefore essential to define a structured framework of indices and indicators, aimed at building a coherent evaluation system that allows the measurement and monitoring of the effectiveness of adaptation and mitigation measures in order to achieve the expected results (Schumann, 2016). These tools make it possible to integrate different scales (building, block, district, city), heterogeneous dimensions and different time horizons, enabling a comparative and multi-scale reading of the performance of the urban system.

In this context, the indicator-based approach is not limited to describing the state of the system, but becomes a knowledge infrastructure for the project, capable of guiding the definition of intervention priorities and supporting the construction of integrated strategies in single and multi-hazard risk contexts.

Indicator based approach

In the international scientific community, the use of indicator-based methodologies for measuring risk adaptation and mitigation has gradually established itself as one of the most effective approaches for addressing the complexity of urban systems, demonstrating the growing interest in these issues (Diaz et al, 2024). In particular, the indicator-based approach is a key activity (UN-ISDR, 2005) and operational tool capable of measuring phenomena that, by their nature, are not directly observable, translating physical, social, economic and environmental dimensions into synthetic and comparable parameters. The indicators act as proxies capable of assessing both the initial conditions (ex-ante), monitoring the evolution of the system over time and evaluating the changes induced by the implementation of adaptation and mitigation strategies and actions (ex-post), providing an objective basis for supporting complex decision-making processes (Kappes et al., 2012). This approach allows for the structuring of the interpretation of the relationships between hazards, vulnerabilities and response capacities, contributing to the obtaining of synthetic, comparable and interpretable parameters capable of supporting the decision-making process in defining and choosing intervention priorities, contributing to the credibility and transparency of the measures defined. Furthermore, the construction of sets of indicators allows quantitative parameters – derived from direct measurements, monitoring and analysis – to be integrated with qualitative indicators, which are necessary to capture contextual aspects, perceptions and socio-cultural components that are not immediately quantifiable. This complementarity is essential in order to provide a complete picture of the risk conditions and the dynamics of adaptability and mitigation of the system. This methodology makes it possible to increase prevention/preparedness for extreme weather events and the ability to combat damage, improving the quality of the built environment and becoming a tool for experimenting with innovative methodologies aimed at building resilient cities (Mussinelli, 2018).

Indicators therefore play a central role not only in assessing the performance of settlement systems in relation to current and future climatic conditions, but also in operationalising concepts such as resilience, adaptive capacity and climate sustainability (Birkmann et al., 2013; Sharifi, 2016). However, their effectiveness depends on the availability of verifiable data, the transparency of selection criteria and the ability to communicate complex results in a simple way, encouraging stakeholder involvement and evidence-based decision-making processes, as well as information sharing. This allows for the comparison of different scenarios and, being objective data, represents a sustainable and scientifically valid value (Canepa, 2018).

Indicators have been used in many fields of application because they are able to capture a wide range of parameters, such as physical, social, and economic ones (White et al., 2024).

In this context, the indicator-based approach finds its preferred operational application in risk assessment, understood as a systematic process of risk identification, analysis, and evaluation. Within this process, indicators are the key tool for making the fundamental components of risk – hazard, exposure, vulnerability and response capacity (Skoulidou & Kazantz, 2025) – measurable and comparable, allowing us to move beyond sectoral readings and construct integrated assessments (Cardona, 2013). The use of structured sets of indicators makes it possible to translate the complexity of urban systems into coherent analytical frameworks that can support both the diagnosis of existing risk conditions and the assessment of the potential effects of adaptation and mitigation strategies over time. From this perspective, risk assessment is not only a cognitive tool, but also a decision-making device capable of guiding the definition of intervention priorities, the comparison of alternative scenarios and the verification of the effectiveness of project actions, especially in contexts characterised by complex and multidimensional phenomena (Bossel, 1999; Singh et al., 2012).

In particular, in the relevant scientific literature, an initial line of research has focused on the construction of sets of indicators for assessing vulnerability and climate adaptation in urban areas. In these contributions, adaptation is interpreted as a multidimensional process involving physical, environmental, social and economic components, and indicators are used to represent the state of the system and its ability to respond to climate stresses. Studies such as those by Birkmann et al. (2013) and Brooks et al. (2005) highlight how the effectiveness of indicators depends heavily on their ability to reflect local specificities and to be constructed in relation to dominant climate risks, avoiding overly generalised approaches.

A second relevant strand concerns the development of indicator frameworks for urban resilience, in which adaptation and mitigation are considered complementary dimensions. In these approaches, indicators are not aimed exclusively at measuring impacts or conditions of vulnerability but take on an evaluative function of the strategies and actions implemented, allowing for the comparison of alternative intervention scenarios. Examples such as Sharifi (2016), Meerow et al. (2016) and Mehryar et al. (2022) highlight how indicator-based urban resilience frameworks allow for the integration of climate, environmental and socio-economic objectives, promoting a systemic reading of urban performance and supporting complex decision-making processes.

Several studies have also highlighted how the traditional separation between mitigation and adaptation indicators limits the ability to capture co-benefits and possible compensation effects between the two dimensions (Dang et al., 2003; Smit & Wandel, 2006). As a result, there is growing interest in integrated indicator-based methodologies capable of simultaneously assessing the effects of project actions in terms of climate mitigation and reducing the vulnerability of exposed systems.

Another area of research concerns monitoring and evaluation (M&E) systems (Dupuits et al., 2024), in which indicators are used to measure not only the implementation of actions, but also their effects on urban systems and long-term changes in relation to climate objectives. Critical reviews show that, despite the spread of such approaches, methodological difficulties remain in relation to the selection of indicators, the standardisation of data and the comparability of results between different contexts (Hinkel, 2011; Bours et al., 2014). These critical issues are particularly evident in integrated risk scenarios, where the coexistence of multiple climate hazards requires assessment tools capable of capturing complex interactions and evolutionary dynamics.

The adoption of adaptation and mitigation indicators is also supported by international and national policies and guidelines, which promote their use in both single-risk and multi-risk contexts. At the international level, the IPCC (2021, 2023) and the UNFCCC (2023, 2025) emphasise the importance of integrated indicators – defined as metric systems designed to combine heterogeneous data relating to different dimensions of a complex phenomenon into a single coherent analytical framework according to a systemic vision (Niemeijer & De Groot, 2008; Riley, 2000) – to monitor the effectiveness of adaptation and mitigation actions in different urban sectors. Through the Green Deal and its reports on climate adaptation, the European Commission encourages the use of territorial and sectoral indicators to assess urban resilience and progress towards climate neutrality. At the national level, several European countries (including Germany, the United Kingdom and Italy) have developed indicator-based frameworks to measure the adaptive capacity and effectiveness of energy and environmental mitigation policies.

These regulatory and policy tools represent a fundamental link between scientific research and governance, facilitating the translation of indicator-based methodologies into operational decisions and project interventions, and encouraging the integrated management of multi-hazard risk scenarios. In this context, it is clear that these methodologies provide support for measuring adaptation and mitigation capacities for the reduction of individual and/or integrated risks, but at the same time they highlight the need for more integrated, multi-scalar and project-oriented approaches. In this sense, indicators should not be understood as mere ex-post verification tools, but as cognitive and operational devices capable of guiding decision-making and planning towards effective and contextually appropriate strategies.

In the context of urban risk assessment, one example is the indicator-based approach applied in relation to the complexity of climate phenomena and the multi-scalar nature of urban systems. In particular, the most recent literature highlights how the effectiveness of indicator-based approaches depends significantly on the consistency between the scale of application, the type of risk considered and the objectives of adaptation and mitigation strategies. The selection and organisation of indicators cannot therefore be separated from a clear definition of the scales of analysis and the dominant climate risks, particularly in contexts characterised by multi-risk scenarios.

For example, at the building level, indicators are mainly geared towards assessing the physical and technological response capacity of the building to various types of stress (e.g. heat waves). This includes energy indicators, such as energy demand or energy class, which measure the performance of the building in terms of energy consumption and efficiency, recognised as key tools for comparing alternative scenarios for decarbonising the building stock (D'Ambrosio et al., 2023). On a larger scale, such as that of the urban district – an intermediate scale between city and neighbourhood – the indicators take on a systemic function, allowing the interactions between buildings, open spaces and infrastructure to be assessed and the cumulative effects of adaptation and mitigation design measures to be read. Indicators such as the Sky View Factor, NDVI, Albedo or LST make it possible to measure the effectiveness of adaptation and mitigation strategies and to interpret the capacity of the urban system to anticipate, absorb and adapt to climate impacts (Meerow et al., 2016; Feldmeyer et al., 2019; Mehryar et al., 2022). At this scale, the indicator-based approach is particularly effective in supporting integrated urban policies and monitoring the effects of adaptation and mitigation strategies over time.

In conclusion, the indicator-based approach is an essential tool for measuring adaptation and mitigation capacities in urban contexts characterised by single and multi-risk scenarios, where the combination of scientific research, policy and operational applications based on multi-scalar indicators geared towards multi-risk is the key to an integrated approach to risk management aimed at building resilient, sustainable and adaptive cities in the long term.

3.2. Multi-platform approach to analyze the effect of mitigation and adaptation policies, strategies and actions in case studies

European cities today face increasingly complex risks, characterised by interconnected phenomena such as heatwaves, floods, earthquakes, etc., which require a rethinking of the tools and policies needed to best reflect this complexity. Urban and metropolitan settlements, as complex socio-technical systems (SETS), exhibit interdependencies between physical, environmental and infrastructural components that render sectoral or single-tool approaches inadequate (IPCC, 2023). The SETS framework defines an analytical and operational approach to managing complexity and urban transformation and construction processes through an understanding of the socio-cultural (S) and ecological-biophysical (E) dimensions, mediated using material and immaterial technologies (T) (Clemente, 2024).

Within this framework, there is a need to develop methodologies capable of integrating multi-scale data, spatial modelling and indicator-based assessment frameworks, with the explicit aim of measuring the effects of risk-oriented policies and actions. In particular, the definition and analysis of mitigation and adaptation policies for risk reduction in urban settlements cannot be limited to a descriptive review of the actions implemented but must be oriented towards a comparative and quantitative measurement of the change in risk induced by the strategies adopted. These produce effects that extend across diverse domains – energy, environment, economy, society and institutions – and operate on different temporal and spatial scales. Consequently, their assessment cannot be entrusted to a single model or a single analytical platform. The proliferation of next-generation platforms demonstrates that it is now essential to have tools capable of aggregating heterogeneous data and supporting integrated assessments of urban risk. These tools enhance transparency and collaboration among stakeholders and enable simulations and comparisons of scenarios with varying intensities and vulnerability conditions.

To this end, the multi-platform approach takes the form of a methodological framework in which multiple models, tools and computational environments – developed for different purposes – are integrated into a coherent analytical system to simulate, measure and compare the effects of packages of measures in real-world case studies.

In particular, the concept of a platform originates in the field of computer science as a technological environment or a set of resources that enable the execution of software applications (Meyer & Seliger, 1998). In this sense, a platform encompasses the system characteristics that provide the functionalities necessary for running applications, designed to be distributed to a large community of users, to offer a wide variety of methodological approaches, with the possibility of being used via an easy-to-use web application (Negulescu et al., 2023).

With the rise of digital platforms, the term 'digital platform ecosystem' has become increasingly widespread (Hein et al., 2020), as has that of 'platform-mediated networks' (Eisenmann et al., 2011), highlighting an evolution in methodologies from single-platform approaches towards studies that consider multiple heterogeneous digital platforms within a single operating system. This shift has led to the emergence of multi-platform approaches, such as integrated systems—often web-based—that connect different models and execution environments, ensuring interoperability and consistency of functionality.

In the literature, the need to link distinct sectoral models stems from the tradition of model coupling and soft-linked integrated assessment models (IAMs), developed to link climate, economic and energy dynamics (van

Vuuren et al., 2011; Weyant, 2017). However, whilst IAMs internally integrate multiple subsystems, the multi-platform approach relies on the interaction between autonomous and specialised platforms, which retain their own architectures and operational logics but are connected through interoperability procedures, data exchange and the harmonisation of indicators. At the same time, the need to assess synergies and trade-offs between climate policies necessitates the joint use of models designed for different domains. Established tools such as CLIMADA (Aznar-Siguan & Bresch, 2019) for climate risk and OSeMOSYS (Plazas-Nino, 2025) for the energy transition were developed for distinct purposes, but today their integration is crucial for analysing the effectiveness of multi-sectoral policy packages.

In the context of risk management and climate impact mitigation, the term 'multi-platform' no longer refers simply to software compatible with multiple systems, but rather to the integration of platforms, models and decision-support tools, each with its own purposes and languages, to tackle complex problems requiring interdisciplinary knowledge. With this approach, it is possible to bring together heterogeneous datasets, decision-making analysis tools and interactive visualisations to support risk assessment and scenario-based planning.

The growing evidence of interactions, synergies and potential trade-offs between adaptation and mitigation necessitates an integrated approach capable of simultaneously assessing direct effects, co-benefits and possible maladaptation phenomena (Sharifi, 2020). From this perspective, the integration of different platforms makes it possible to overcome analytical fragmentation and build a coherent pathway linking data, indicators, and decisions. The multi-platform approach allows for the integration of mitigation and adaptation within a single assessment framework, enables operation at various scales – from the building to the district level – and ensures replicability with open-source data and transparent procedures. In a context of growing complexity and multiple risks, the ability to quantitatively measure the change in risk induced by climate policies represents a crucial step in the transition from declarative strategies to genuinely climate-proof strategies, grounded in empirical evidence and geared towards the systemic reduction of urban vulnerabilities.

The multi-platform approach, therefore, can integrate various tools, models, data sources and stakeholder methods to assess the effectiveness of mitigation and adaptation policies, representing a more advanced paradigm for holistically and robustly evaluating the effectiveness of mitigation and adaptation policies, strategies and actions in contemporary urban contexts.

3.3. Adaptation and mitigation solutions catalogues for urban resilience in multi-risk scenarios

Transforming urban settlements and open spaces into resilient and regenerative systems is a key, cross-cutting objective in which design and innovation must come together to minimise the impacts and vulnerabilities arising from extreme weather events.

In particular, the evaluation of design alternatives and the identification of the most effective solutions – based on specific needs and critical issues – become a fundamental step in the transition of urban districts towards resilient and regenerative eco-districts (Mussinelli & Tartaglia, 2021). The growing complexity of urban settlements and the interdependence of their components make it necessary to consider design interventions as mechanisms capable of generating environmental, economic and social co-benefits. The IPCC has defined co-benefits as 'the positive effects that a policy or measure aimed at one objective mighthave on other objectives, thereby increasing the total benefits for society or the environment' (IPCC, 2018). In the context of the transition towards resilient and regenerative eco-districts, design interventions are not limited solely to reducing the impacts of hazardous events, but trigger a range of co-benefits that have the potential to reduce the negative impacts of climate change on human and ecological health, including economic factors and social capital (Spencer et al., 2017).

Studies on resilience in urban settlements have progressively shifted from the implementation of interventions targeted at single-risk scenarios to sets of standard interventions/solutions capable of having effective positive impacts in multi-risk scenarios. The scientific literature offers both thematic toolkits and formal decision-support frameworks that bring together adaptation and mitigation measures for urban resilience in multi-risk conditions. Numerous sources can be found reporting on or related to the effects of reducing the impacts of heatwaves, flash flooding or combined risks (such as earthquake-flood events). However, gaps remain in harmonised multi-hazard taxonomies and in the systematic assessment of long-term trade-offs and maladaptation phenomena across different urban contexts.

In this context, scientific literature has developed various methodological approaches in recent years aimed at assessing adaptation and mitigation measures for the resilience of urban settlements, taking into account different hazards, performance-based responses and co-benefits.

For example, within the RESCCUE project, with a view to achieving resilience objectives at the urban scale – understood as the capacity of a system, community or society exposed to hazards to withstand, absorb, adapt to and recover from the impacts of an adverse event, including through the preservation and restoration of its essential structures and functions (UNISDR, 2009) – it identifies specific adaptation strategies, consisting of one or more general measures, aimed at addressing current and future climate impacts in urban areas. It identifies three variables for selecting adaptation strategies: the estimated cost of the strategies, the co-benefits and the reduction in post-event recovery times.

In practical terms, to assess the reduction in urban impacts that a given adaptation measure or strategy can generate, the RESCCUE project proposes a matrix that links 32 urban services with 5 types of risk (namely flooding, CSO, drought, heatwaves and sea-level rise) to be associated with each adaptation measure. In the matrix, the city's overall level of resilience is assessed based on the effectiveness of the selected measure in relation to the affected urban services, but also in relation to the extent to which it may compromise the resilience of urban services interacting with those directly affected.

Another significant initiative is the Catalogue of Nature-based Solutions for Urban Resilience developed by the World Bank as part of the Global Programme on Nature-based Solutions and the City Resilience Programme. In response to the growing interest in and demand for NBS, the catalogue of solutions was developed as a guidance document enabling an initial identification of potential investments in such solutions, providing technical descriptions, visualisations and examples to assess the benefits of NBS in urban areas. It includes estimates of unit costs and benefits to support the assessment of economic feasibility, and suitability criteria to guide the identification of potential locations for NBS. From a multi-risk perspective, the catalogue focuses primarily on NBS for managing the risk of flooding and heatwaves in urban areas, but also provides guidance on further social and environmental benefits of the identified solutions.

To support climate change adaptation and mitigation policies in land-use sectors, the LAMS Catalogue – developed as part of the RethinkAction platform – has been created: an interactive, scientific repository of place-based climate solutions. The catalogue was compiled with the input of experts and based on an extensive literature review, and can be used independently by various stakeholders as a knowledge base or as input for decision-making processes and modelling tools for the development of climate change adaptation and mitigation policies.

For the comparative assessment of typical solutions, a significant contribution was also made by the European CLARITY project, which developed a Climate Services Information System (CSIS) aimed at supporting urban planning through the integration of climate data, risk models and tools for evaluating adaptation measures (Zuccaro & Leone, 2021). Within this framework, technical solutions are analysed using screening procedures and multi-criteria analysis that include the assessment of co-benefits associated with interventions. In particular, the system allows for the simulation of urban transformation scenarios and the estimation of the effects of design strategies across various impact domains, integrating indicators relating to climate risk reduction with environmental, economic and social parameters.

As part of the research activities, in order to guide adaptation and mitigation strategies for the resilience of urban eco-districts, an approach has been developed to define standard interventions that can be replicated in all urban contexts, in ways compatible with the morphological conditions underpinning the urban layout and with the architectural characteristics defining the articulation of the perimeter of open spaces.

From a methodological perspective, the catalogue of standard interventions (see DV 4.4) begins with the identification of recurring urban components in urban open spaces (axes, squares, plazas, green areas, courtyards, car parks). Four categories of intervention, derived from the scientific literature, have been associated with each component: vegetation, soil, water and urban facilities. These categories are interpreted as active climate control measures, capable of simultaneously influencing thermal regulation, shading, evapotranspiration and water management. In addition, a compound scenario has also been defined, representing the result of individual design actions implemented simultaneously across each of the four previously defined areas. Their combination can contribute to the construction of an urban climate infrastructure capable of mitigating the impacts of hazardous events – such as heatwaves and flooding – whilst simultaneously improving the quality of public space. The integration of the four categories of intervention therefore allows open space to be configured as an integrated climate system, capable of acting simultaneously on various environmental processes and contributing to the creation of resilient and regenerative eco-districts. For each combination, three categories of co-benefits are also assessed qualitatively: environmental, economic and social. These three categories of co-benefits play a crucial role in facilitating the transition towards resilient and regenerative eco-districts, creating opportunities that can offset negative impacts on different sectors whilst ensuring social inclusion and equity, economic diversification and environmental sustainability. Specifically, within the research, the assessment of co-benefits associated with interventions to transform urban open space was developed using an approach aimed at highlighting the impacts generated across the main domains of urban sustainability. The proposed approach does not aim to provide an absolute quantification of performance, but rather to offer a comparative analysis of different design strategies, highlighting the multifunctional nature of the interventions and their potential contribution to the transition towards more resilient and regenerative urban settlements.

3.4. Towards the definition of a methodology to characterize what-if scenarios

In this paragraph is described the methodology applied to evaluate the efficacy of actions applied in what-if scenarios.

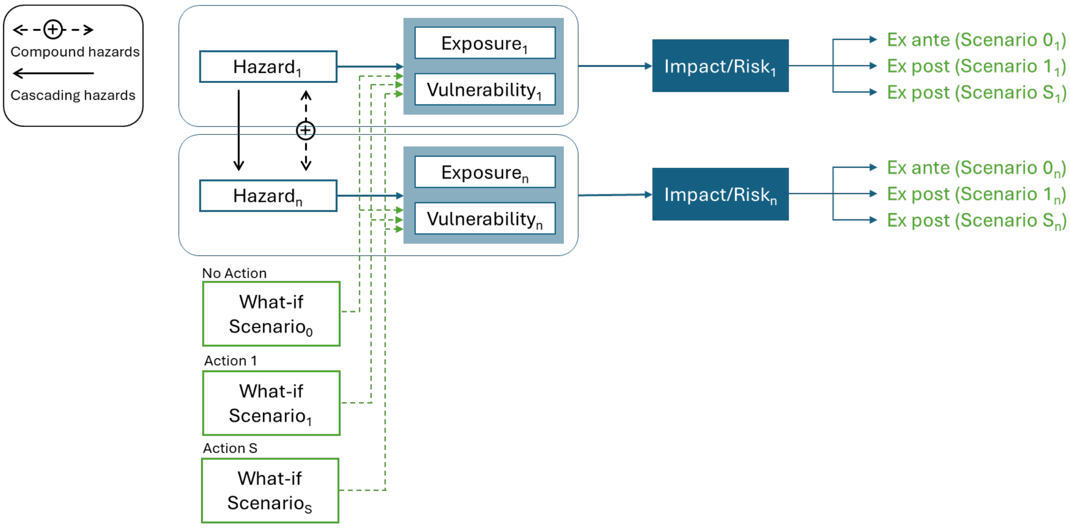

Figure 4. Architectural scheme of the method proposed to assess the resilient effectiveness of actions applied in what-if scenarios.

This framework can be applied both for compound and cascading hazards. It is independent from the models used to evaluate the risk/impact generated by a hazard scenario.

Let Hazard$_1$,…, Hazard$_S$ be S hazard scenarios generated by the occurrence of n climatic, seismic, natural or environmental phenomena. For each hazard scenario is executed a model in which Hazard Exposure and Vunerability indices are measured to evaluate the impact/risk on the study area.

Let suppose we desire to evaluate the effectiveness in the reductions of the impact/risks generated by the occurrence of the n phenomena of a set of actions. The application of a set of actions provides a what-if scenario that produces variations in the measure of Exposure and Vulnerability in each model.

A what-if scenario called What-if Scenario$_0$ is the scenario in which no action is applied to reduce the impact/risks. It generates, for each phenomenon, an ex-ante scenario where no adaptation or mitigation action is implemented. This scenario applied to the *jth* phenomenon called Scenario J$_o$.

The effectiveness of the actions applied in the *ith* what-if scenario, called What-if Scenario$_{i,}$ is measured comparing the impact/risk of the *jth* phenomenon resultant in the corresponding ex-post scenario J$_i$ with the one in the corresponding ex-ante scenario Scenario J$_o$.

The decision maker can evaluate the effectiveness to reduce the impact-risk generated by each phenomenon of each set of actions to decide which set of actions is most effective.

In the example of Fig. 5 this evaluation is done comparing the spatial distribution of impacts/risks determined in the ex-ante scenario with that obtained in an ex-post scenario in which a set of adaptation and simulation actions was simulated.

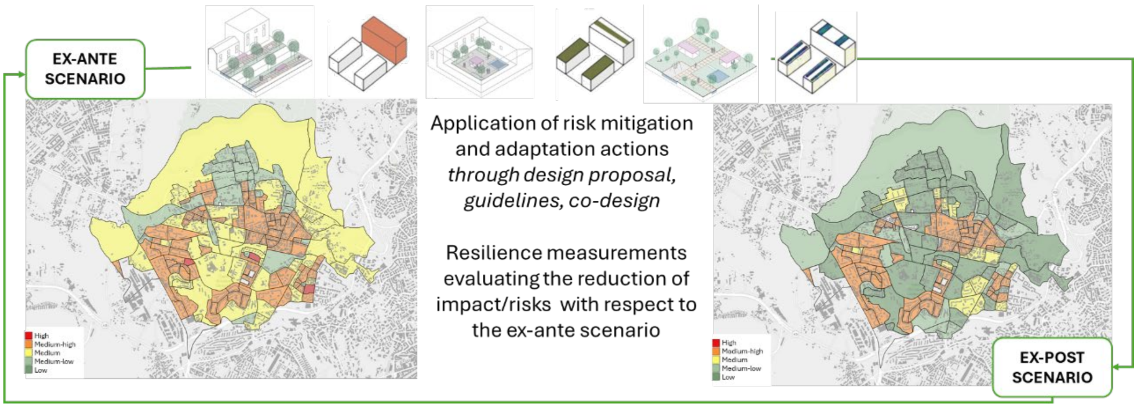

Figure 5. Example of evaluation of the effectiveness of a set of actions comparing the impact/risks assessed in the ex-ante and the ex-post scenarios.

To evaluate, from a multi-hazard perspective, the effectiveness of the set of actions of a what if scenario in the adaptation/mitigation with respect to multiple phenomena, a model labelled MUHRA (MUlti-Hazard Risk Assessment) has been developed. This model is schematized in Fig. 6. It was built starting from the general method shown in Fig. 5.

The resultant single impacts generated by the occurrence of multiple natural phenomena are aggregated by using an aggregating operator, forming the synthetic impact ex ante scenario.

In the diagram in the figure, the Design Solution Category component represents the set of design solutions for a what-if scenario; their applications will bring about changes to the urban settlement elements that will impact the determination of vulnerability and/or exposure.

To assess the resilient effectiveness of the set of intervention actions defined in the what-if scenario, the model is re-executed to reconstruct the synthetic impact scenario ex post. Resilient effectiveness is assessed by comparing the synthetic impacts achieved in this scenario with those achieved in the ex-ante scenario.

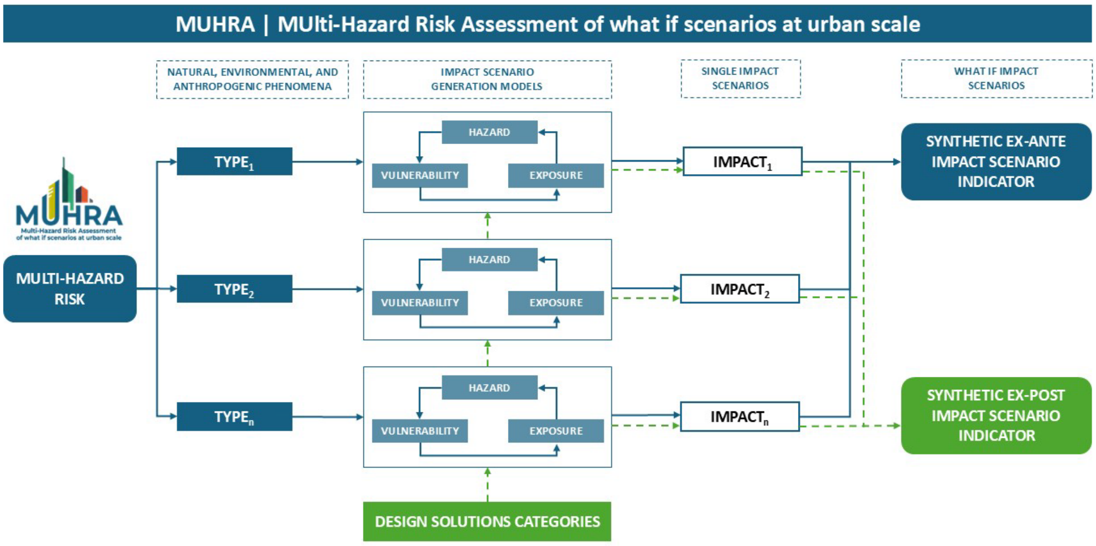

Figure 6. Schema of the model MUHRA - Multi-Hazard Risk Assessment of what-if scenarios at urban scale.

The synthetic impact scenario is obtained using aggregation operators of the impact values determined for each hazard phenomenon. An aggregation operator is understood as an operator that receives individual impact scenarios as input to provide an impact scenario in which each spatial entity is assigned an aggregate impact value or label. The choice of an aggregation operator can range from simple statistical operators such as maximum, minimum, or average, to nonlinear aggregation operators such as computational intelligence clustering, classification, or regression approaches.

Furthermore, the impact model can consider an impact chain that evaluates the interrelationships and cause-and-effect relationships between different hazards. For example, a heat wave, in addition to posing health risks to the population, can lead to increased energy consumption and atmospheric CO$_2$ concentrations due to the excessive use of cooling systems. The assessment of the synthetic impact scenario can take all these effects into account; the assessment of synthetic impacts, in this case, is carried out by considering both the direct impacts and the indirect impacts generated, through a domino effect, by the occurrence of the natural, environmental and anthropogenic phenomena analyzed. Figure 7 shows an example of impact chain modeled in MUHRA.

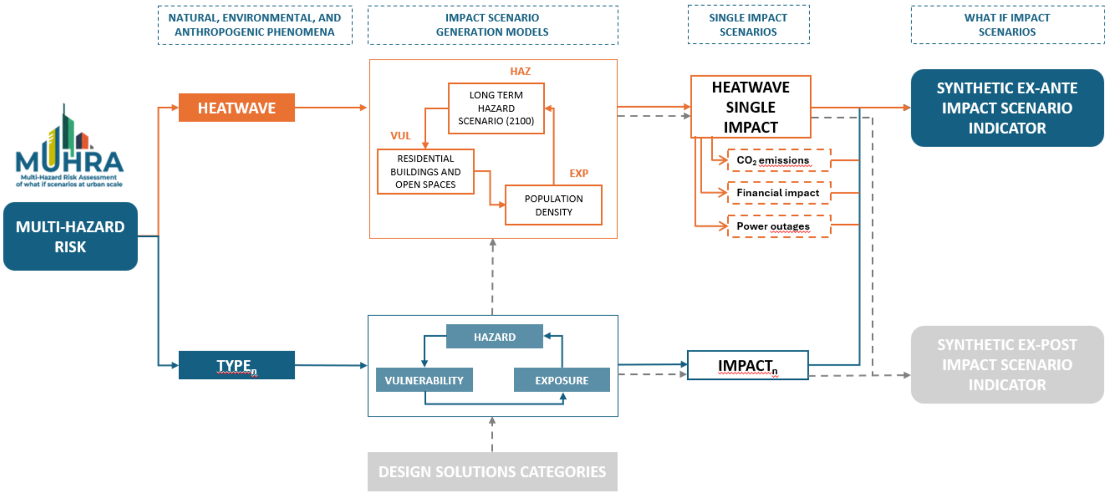

Figure 7. Example of impact chain analysis applied in the MUHRA model.

A comprehensive evaluation of the effectiveness of the project actions in the what-if scenario can include a cost analysis of the interventions and a cost-benefit measurement, determining the benefits both in terms of reduced impacts/risks and in terms of additional benefits, such as reduced energy costs and improved service efficiency.

Since each risk-impact assessment model is treated as a black box, MUHRA can also incorporate multi-hazard models in which the impact/risk assessment processes for the different hazard scenarios are already integrated. These models in MUHRA are treated as a single impact/risk assessment model that will generate a single impact scenario. Figure 8 shows an example of multi-hazard risk model treated in MUHRA; it integrates a multi-hazard impact evaluation model referred to the two compound phenomena heat wave and earthquake.

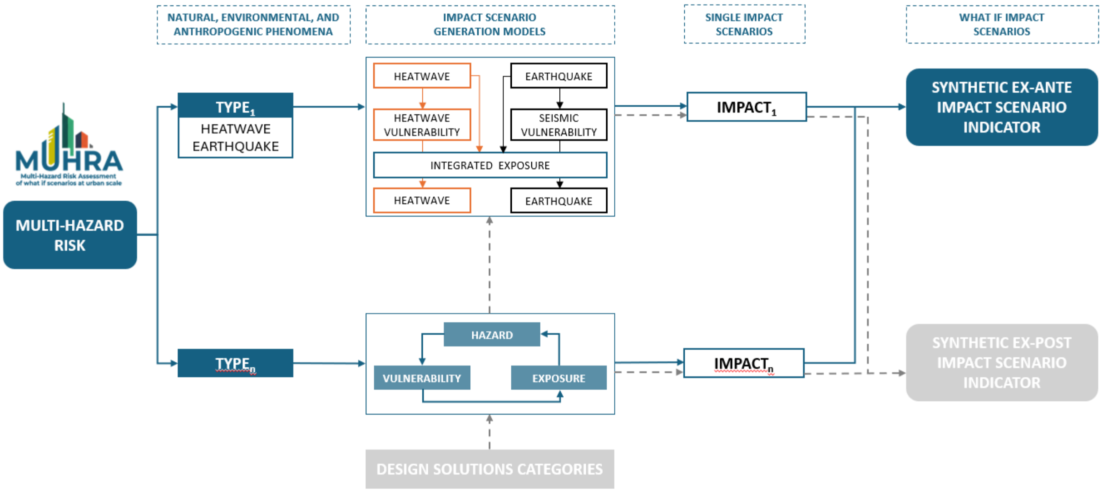

Figure 8. Example of multi-hazard impact/risk model encapsulated in MUHRA.

The following section reports and discusses case studies in which what-if scenarios were developed with design solutions, evaluating their resilient effectiveness by comparing the ex-ante scenario with the generated ex-post scenarios. For each case study, the design actions of the what-if scenario, the resulting ex-post scenarios, and the indices/indicators used to measure the resilient effectiveness of the solutions are briefly described.

4. Case-study collection of applications of the MUHRA model

The research groups involved in the project provided case studies based on what-if scenarios relating to the application of the MUHRA model. For each example, a structured sheet was developed.

Table 5.Case study collection of what-if scenarios

CASE STUDY	REFERENCE AUTHOR	HAZARD CONSIDERED	SCALE
Heatwave and pluvial flooding risks in urban areas. A testing in Naples East Area	M.F. Clemente[1], L. Cozzolino[2], V. Miraglia[1], G. Varra[2], S. Verde[1] [1]DiARC – Department of Architecture, University of Naples Federico II [2]Department of Engineering, University of Naples “Parthenope”	Heatwave Pluvial Flooding	Macro-district
Heatwave vulnerability assessment. A digital workflow to assess ex ante and ex post scenarios in Soccavo district	G. Mangano[1], V. Miraglia[1], S. Verde[1] [1]DiARC – Department of Architecture, University of Naples Federico II	Heatwave	District

A multifactorial holistic indicator for the monetization of natural capital (VCU) as a multiplier of social added value and relational goods: a method, rather than a model, of SROI integrating CBA. Climate Resilience as a Relational Common: deconstructing the cost of inaction through Integrated Nature-Based Solutions in Soccavo, Naples.	R. Cirillo[1] [1]DiARC – Department of Architecture, University of Naples Federico II	Heatwave Pluvial Flooding	Macro-district
Climatic and geophysical risks in urban areas. A testing in Bagnoli, Naples	M.F. Leone[1,2,3], M.T. Girardi[1,2], A. Pallotta[2,3] [1]DiARC – Department of Architecture, University of Naples Federico II [2]Centro Studi PLINIVS-LUPT [3]Urban Climate Change Research Network European Hub	Heatwave Pluvial Flooding Seismic Volcanic	District
Impact chain method to evaluate heatwave impacts	M.F. Clemente[1], S. Puzone[1], S. Verde[1], E. Tersigni[1] [1]DiARC – Department of Architecture, University of Naples Federico II	Heatwave	Macro-district

4.1. Heatwave and pluvial flooding risks in urban areas. A testing in Naples East Area

WHAT-IF SCENARIOS CASE STUDY COLLECTION measuring the effect of multi-risk mitigation and adaptation					
Heatwave and pluvial flooding risks in urban areas. A testing in Naples East Area					
Maria Fabrizia Clemente, Luca Cozzolino, Vittorio Miraglia, Giada Varra, Sara Verde					
RESEARCH UNIT					
V. D’Ambrosio[1], F. Di Martino[1], M.F. Clemente[1], V. Miraglia[1], G. Santomartino[1], E. Tersigni[1], S. Verde[1] [1]DiARC – Department of Architecture, University of Naples Federico II L. Cozzolino[2], G. Varra[2], N. Napolano[2], R. Della Morte[2] [2]Department of Engineering, University of Naples “Parthenope”					
TASK RETURN					
Task 5.5.3 - The resilient-city simulation test of mitigation and adaptation scenarios					
RESEARCH OBJECTIVES					
The aim is to develop a novel method based on the MUHRA model for assessing the resilient capacity of climate proof actions in reducing heatwave and pluvial flooding risks in urban areas. The method performs risk assessments of impact scenarios, both ex ante and ex post, evaluating the reduction of impacts generated by urban climate resilient design interventions. What-if scenarios are tested to assess the potential effects of building retrofit interventions aimed at mitigating the impacts of heatwaves and pluvial flooding in the east districts of the city of Naples.					
KEYWORDS					
1-5 keywords					
SCALE					
☐ territorial	**X** macro-district	☐ district	☐ census zone		
URBAN CONTEXT					
☐ city centre	☐ historic centre	☐ industrial area	☐ periurban area	**X** periphery neighbourhood	

RISK MITIGATED					
X heatwave	**X** Pluvial flooding	☐ Seismic			

SCENARIO ANTE

HEATWAVE

The ex-ante heatwave impact scenario represents a long-term assessment (2071–2100) developed with reference to a specific hazard scenario of the climatic phenomenon "heatwave," acting upon the urban system under investigation for its vulnerability.

The impact scenario was derived by applying a time-dependent emission model consistent with the greenhouse gas emission pathways defined in the IPCC Fifth Assessment Report (AR5, 2014), namely the Representative Concentration Pathways (RCPs). For this analysis, the RCP 4.5 scenario was adopted, which assumes a mitigation of greenhouse gas emissions without a corresponding reduction in their atmospheric concentrations. As a result, concentrations are projected to continue increasing over the next five decades, making it unlikely that the objectives of the 2016 Paris Climate Agreement will be achieved.

The impact scenario is further associated with the concept of exposure, which defines the value and extent of elements at risk from the heatwave-related climatic hazard. The impact is assessed in terms of the population density affected, calculated for each census section.

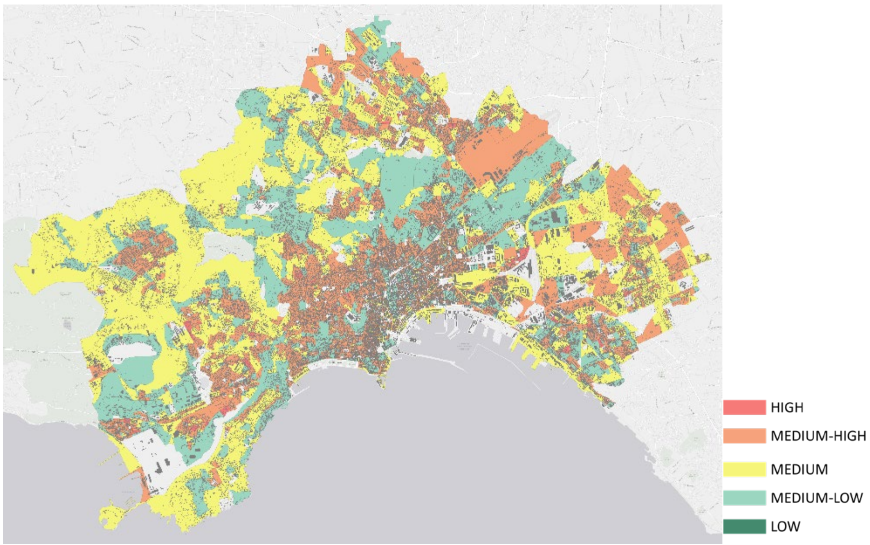

Figure 9. Heatwave ex ante impact

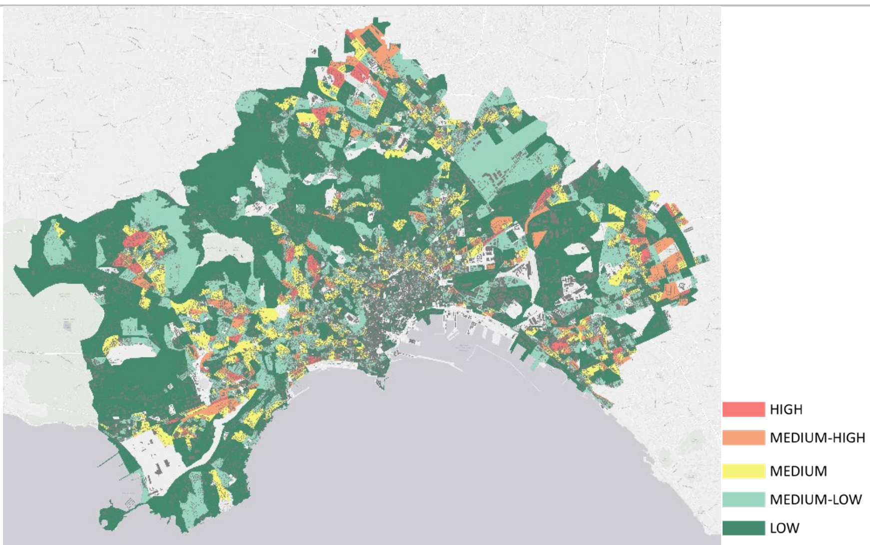

Figure 10. Pluvial flooding ex ante impact

PLUVIAL FLOODING

The ex-ante pluvial flooding impact scenario carried out assesses the potential effects and the consequent impact of small return period (T =10 years) rainstorms compatible with frequent but non negligible damage and widespread flooding.
The impact scenario is constructed by considering the local climate through the Intensity-duration-frequency curve, which in turn is used to implement synthetic hydrographs that are supplied as boundary conditions to a hydrodynamic model for the simulation of ponding and runoff flow throughout the case study urban area. The exposure is measured in terms of resident population at the level of census section, while the vulnerability of the population is correlated with the measure of the flow depth in the census sections.

SYNTHETIC IMPACT

The overall impact (synthetic impact) results from the combined effects of heatwaves and pluvial flooding. It relies on the use of the ISTAT census sections as the core spatial unit.

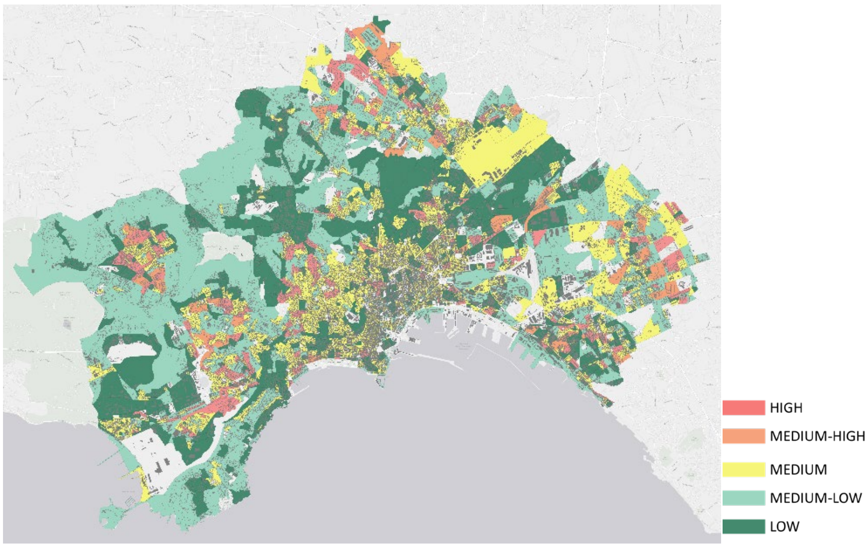

Figure 11. Synthetic ex ante impact

METRICS ANTE

HEATWAVE

Hazard

The hazard scenario was defined with reference to the RCP 4.5 emission pathway described in the IPCC Fifth Assessment Report (AR5), assuming a long-term heatwave event occurring in the period 2071–2100, with a maximum duration of 60 days.

The characteristics that define a hazard scenario can be categorized into temporal and spatial features. The temporal features are represented by daily climatic parameters, namely the maximum and minimum air temperatures and the relative humidity. These three parameters are used to calculate the Heat Index (HI), as defined by the U.S. National Weather Service. A heatwave event is identified when the HI exceeds 32 °C for at least three consecutive days.

The spatial features of the hazard are derived from remotely sensed surface temperature raster data collected during a heatwave, monitored both during the day and at night. The most critical areas are identified by measuring the difference between daytime and nighttime temperatures: the smaller this difference, the higher the associated hazard level.

Vulnerability

Vulnerability is evaluated through a systemic approach that conceptualizes urban settlements as systems composed of multiple, overlapping, and interacting subsystems. The assessment framework and indicators are structured accordingly to capture the interrelations among these components. The vulnerability to the heatwave of the buildings subsystem is assessed using four intermediate indicators:

- thermal lag,
- thermal decremention factor,
- building volume,
- solar exposure of building envelope.

Instead, for the outdoor space subsystem, the intermediate indicators are:

- Albedo,
- Sky View Factor,
- Solar Exposure of Outdoor Spaces,
- Normalized Difference Vegetation Index (D'Ambrosio et al., 2023b).

Exposure

The exposure is assessed in terms of Population density (PD), and it is aimed at identifying the spread of the population in the study area and highlighting the degree of crowding in that area

PLUVIAL FLOODING

The metrics used for the assessment of the ex-ante pluvial flooding impact scenario are based on the evaluation of the pluvial flooding hazard, which considers surface water depths generated by rainfall events with a 10-year return period. The hazard is then correlated, at the census section scale, with the resident population density, resulting in a final flooding risk indicator.

Hazard

The hazard scenario consists of a pluvial flooding map (flood extension and depth) enveloping the inundation maps corresponding to different synthetic rainfall hyetographs with return period $T = 10$ years. The flooding map results from the application of a hydrodynamic model (two-dimensional non-inertia wave equations) taking into account topography and building distribution, infiltration of the rainfall through the soil and the artificial surfaces, soil and surface roughness, and the time and space distribution of the hyetographs. In the following, the materials and methods necessary to define the hazard scenario are briefly recalled.

Mathematical and numerical model

For the sake of simplicity, the mathematical model chosen for the hydrodynamic simulation is the two-dimensional non-inertia wave, able to simulate the evolution of hydrodynamic variables such as flow depth and horizontal components of the velocity under predefined boundary conditions (a real or a synthetic hyetograph), taking into account topography and building distribution, infiltration of the rainfall through the soil and the artificial surfaces, soil and surface roughness. The numerical model used is HEC-RAS 6.7 from US Army Corps of Engineers. The Curve Number method is used for the simulation of infiltration processes while the Manning's formula is applied to compute flow resistance.

Synthetic hyetographs

Using the historical rainfall depths measured with a 10-minutes time interval at relevant rainfall stations managed by Protezione Civile Regione Campania in the area of Naples (Nisida, Pozzuoli, Camaldoli, Capodimonte, Torre del Greco, Ercolano), a unique intensity-duration-frequency curve is attributed to the Naples metropolitan area by means of an inverse distance weighting interpolation. Using the alternating-block method, 4 synthetic hyetographs are constructed with return period $T = 10$ years and durations $d = 0.5$, 1, 3, and 6 hours. The inundation model is run for each of the hyetographs and the flow depths are subsequently enveloped.

Roughness, infiltration

The land use map from the Copernicus Land Monitoring Service Urban Atlas 2018 service supplies a characterization of the natural and artificial surfaces in the study area, based on the building density and the human activities attributed to the relevant elements of the land use map. This allows to characterize the surfaces and the soils by means of a Curve Number for the computation of the infiltration effects and by means of a Manning's roughness coefficient to be used in the hydrodynamic computations.

Drainage network modelling

The topologic and geometric information (channel connections, diameter, slope and roughness of pipes, geometry of manholes, number, position, and typology of inlets) relative to urban drainage network of the case study area is scarce or not available. The pragmatic approach adopted, inspired from the scientific literature, treats the inlets as an additional infiltration capacity attributed to artificial surfaces (roofs, streets, sidewalks, parking lots, squares). In the context of the Curve Number approach, the Initial Abstraction parameter is set to ensure that the surfaces can entirely absorb the rainfall depth extracted from the IDF curve for a duration d equal to the duration of the hyetograph applied and a return period equal to $T = 2$ years.

Vulnerability

In the present approach, vulnerability to pluvial flooding is a step function of space assuming the values 0 in the points of the inundated areas where the inundated depth is smaller or equal to 5 cm, while it assumes value 1 in the points where the flow depth is greater than 5 cm. It is assumed that a 5 cm flow depth at the ground is sufficient to inhibit the movement of pedestrians and slow down vehicular circulation, interfering with emergency rescue vehicles. At the level of census section, the vulnerability is assumed as the areal average of the point vulnerability.

Exposure

For the sake of simplicity, the exposure in each area is determined by the population resident in the census section.

SCENARIO POST

HEATWAVE

The ex-post heatwave impact scenario is developed by assuming the implementation of technological retrofit interventions on the buildings located within the study area.

These interventions are aimed at reducing the vulnerability of the "Buildings" subsystem with respect to the heatwave hazard. The considered retrofit measures include:

- External thermal insulation
- Extensive green roof
- Fixed shading system
- Replacement of window frames
- Reversible air-to-water heat pump
- Photovoltaic system.

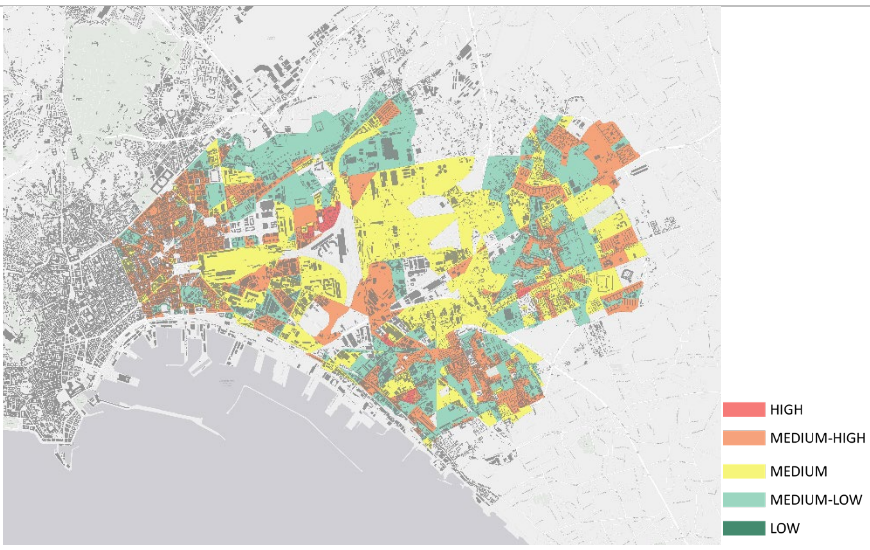

Figure 12. Heatwave ex post impact

PLUVIAL FLOODING

The ex-post pluvial flooding impact scenario involves the application of the green roof system on buildings identified as suitable for its implementation. Suitability of the buildings is determined by age of the buildings (monuments and historical buildings are excluded), available surface on the roof (at least 300 m2), constructive type (reinforced concrete buildings).

In the context of the numerical model used (HEC-RAS 6.7), the green roofs are modelled using the Curve Numbers from the literature, complemented by the innovative use of Initial Abstraction coefficients that take into account the retention ability of green roofs and their cascading with the drainage network system.

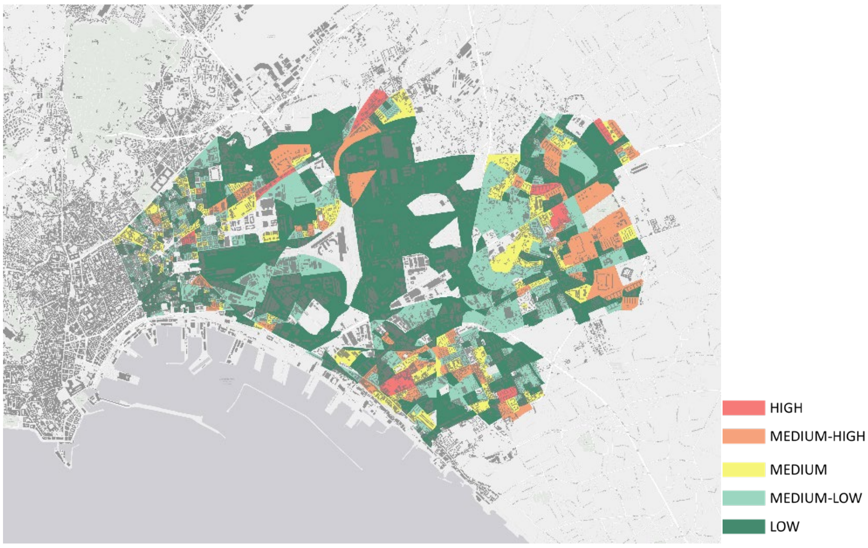

Figure 13. Pluvial flooding ex post impact

SYNTHETIC IMPACT

The ex post overall impact (synthetic impact) results from the combined effects of heatwaves and pluvial flooding. It relies on the use of the ISTAT census sections as the core spatial unit.

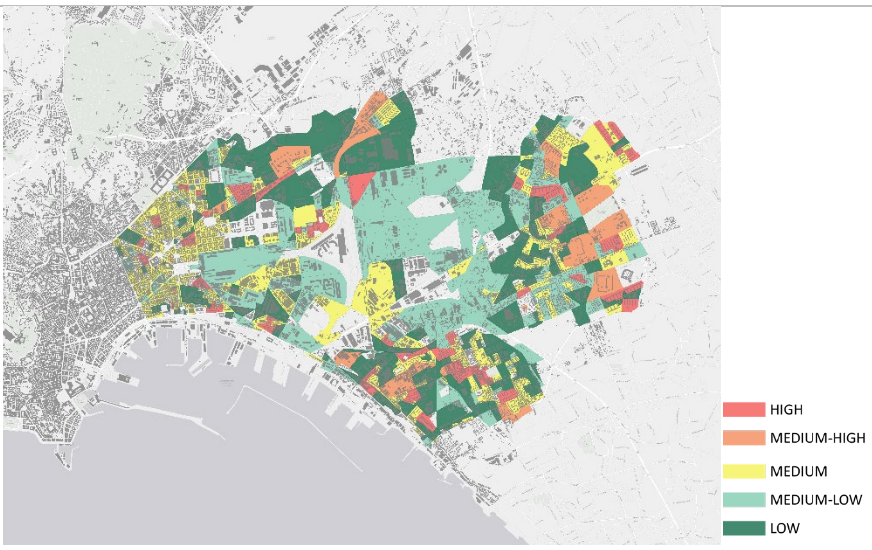

Figure 14. Synthetic ex post impact

METRICS POST

HEATWAVE

The indicators used for the assessment of the ex-post heatwave scenario are the same as those adopted for the ex-ante scenario, recalculated under the assumption of implementing active and passive technological retrofit interventions on buildings aimed at mitigating the impacts of heatwaves.

Interventions on the building envelope, and subsequently on the building systems, also enable the optimization of energy consumption and contribute to the reduction of CO_2 emissions. The estimation of CO_2 emissions is based on the identification of the most recurrent and representative building typologies within the census sections.

The simulation of the energy demand and CO_2 emissions for the sample buildings was carried out using the MasterClima MC 11300 software, based on the construction techniques reported in the Catalogue of Common Building Techniques. The input of data related to the building envelope and systems allowed the simulation of CO_2 emissions, the reference energy performance class, and the primary energy demand for heating, domestic hot water, and cooling.

PLUVIAL FLOODING

The metrics used for the assessment of the ex-post pluvial flooding impact scenario are the same as those adopted for the ex-ante scenario, recalculated following the application of the green roof intervention on the selected buildings.

SYNTHETIC IMPACT

The metrics used for the assessment of the ex-post synthetic impact scenario concern the between the ex ante and ex post synthetic impact classes for ISTAT census sections.

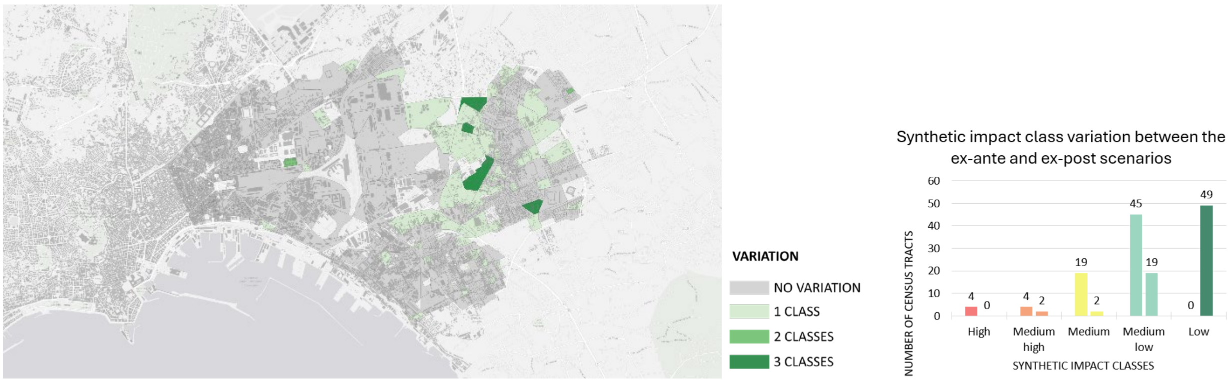

Figure 15. Synthetic impact class variation between the ex ante and the ex post scenarios

TOOLS

X GIS Suite ESRI ArcGIS Pro	☐ …	☐ …		

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4.2. Heatwave vulnerability assessment. A digital workflow to assess ex ante and ex post scenarios in Soccavo district

WHAT-IF SCENARIOS CASE STUDY COLLECTION

measuring the effect of multi-risk mitigation and adaptation

Heatwave vulnerability assessment. A digital workflow to assess ex ante and ex post scenarios in Soccavo district

Giuseppe Mangano, Vittorio Miraglia, Sara Verde

RESEARCH UNIT

V. D'Ambrosio[1], F. Di Martino[1], M.F. Clemente[1], V. Miraglia[1], G. Santomartino[1], E. Tersigni[1], S. Verde[1]

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TASK RETURN

Task 5.5.3 – the resilient-city simulation test of mitigation and adaptation scenarios

RESEARCH OBJECTIVES

The goal of the experimentation is to develop a model to evaluate what-if scenarios – generated by the application of climate-proof solutions – through the assessment of heatwave vulnerability reduction of the open spaces. The model assesses the vulnerability of urban open spaces to heatwaves, implemented within an IT-based assessment workflow, and conceptualises adaptation as a measurable process through what-if scenarios.

KEYWORDS

Climate-proof design, digitals tools, nature-based solutions, GIS-based workflow

SCALE

☐ territorial	☐ macro-district	☒ district	☐ census zone		

URBAN CONTEXT

☐ city centre	☐ historic centre	☐ industrial area	☐ periurban area	☒ periphery neighborhood	

RISK MITIGATED

☒ heatwave	☐ Pluvial flooding	☐ Seismic	☐ …		

SCENARIO ANTE

The ex-ante impact scenario for the heatwave phenomenon on open spaces is developed with reference to the hazard analyses of a series of microclimatic factors, on the urban system of Soccavo (Naples) for the current (2024), short-term (2030), and medium-term (2050) climate scenarios.

The impact scenario is also associated with the concept of exposure, which defines the magnitude and extent of the elements at risk in relation to the climate hazard associated with heatwaves. The impact is assessed in terms of the affected population density, calculated for each census tract and cross-referencing the main microclimatic indices to assess heat stress in the categories of child, woman, man, and elderly.

The ex ante scenario assumes that the situation of open spaces in the Soccavo district stays the same as it is today, without any climate-proof measures applied.

METRICS ANTE

The modeling of the physical and microclimatic behavior of the open spaces in the urban area of Soccavo, in the ex-ante impact scenario, is enhanced by the analysis of factors associated with heatwave hazard, including the increased albedo effect, the urban heat island phenomenon, thermal discomfort, and the intensification of solar radiation on land surfaces. This analysis is carried out through the calculation of biometeorological indices linked to thermal comfort measurements, such as Mean Radiant Temperature (MRT), Predicted Mean Vote (PMV), Predicted Percentage of Dissatisfied (PPD), Physiological Equivalent Temperature (PET), and Universal Thermal Climate Index (UTCI).

For the open space subsystem, the intermediate indicators to assess heatwave vulnerability are:

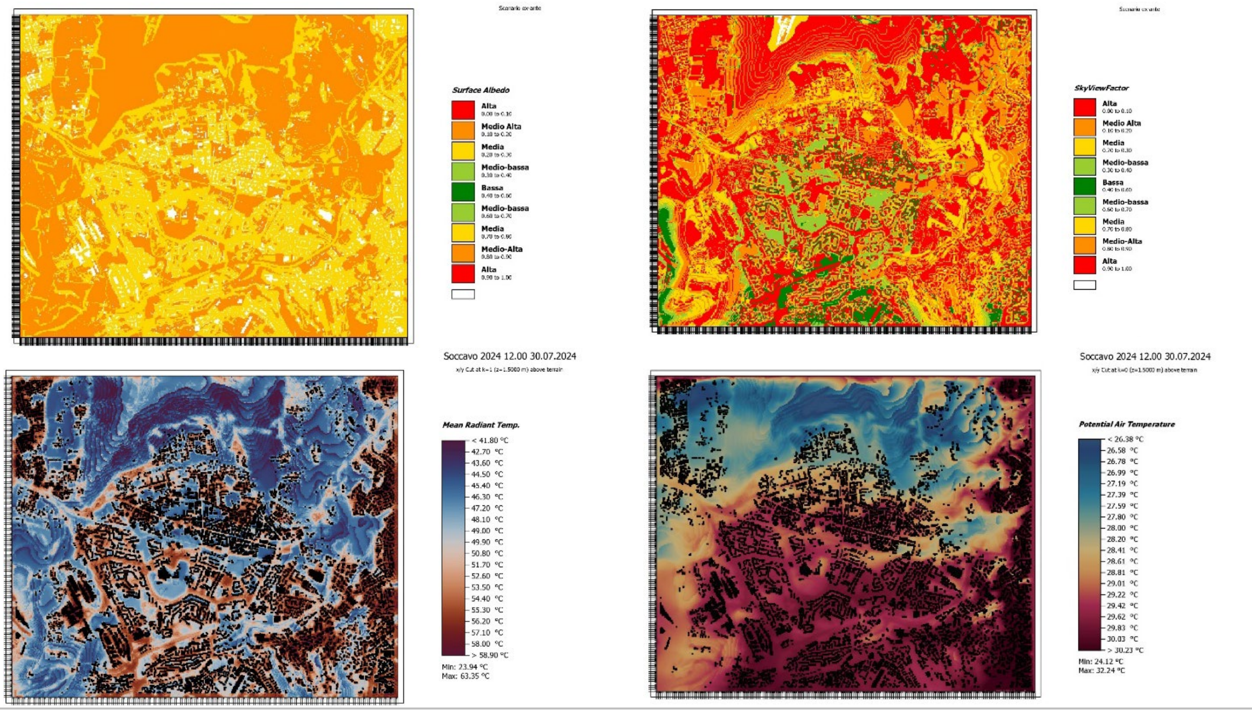
a) Albedo
b) Sky View Factor (SVF)
c) Hillshade (of opens spaces)
d) Normalized Difference Vegetation Index (NDVI).

In addition, the evaluation of the vulnerability of open spaces has been further developed through the modelling and simulation of the following aspects:

a) Physiological Equivalent Temperature (PET)
b) Predicted Mean Vote (PMV)
c) Predicted Percentage of Dissatisfied (PPD)
d) Mean Radiant Temperature (MRT)
e) Universal Thermal Climate Index (UTCI)
f) Potential Air Temperature (PotAT) – height 1,5 m.

The study adopts a systemic approach, treating urban settlements as a network of interacting subsystems. To capture these interrelations, vulnerability is measured through specific morphological and environmental indicators: Albedo, Sky View Factor (SVF), Hillshade, and NDVI. These metrics evaluate the settlement's character based on its typology, technology, and green infrastructure density.

Albedo and SVF were analysed using ENVI-met at a 10x10 m resolution (district/basin scale). Simulations incorporated the SSP3-7.0 medium-to-high emissions pathway, projecting climatic conditions for 2024 (baseline), 2030, and 2050. ENVI-met was also used to simulate Physiological Equivalent Temperature (PET), Predicted Mean Vote (PMV), Predicted Percentage of Dissatisfied (PPD), Mean Radiant Temperature (MRT), Universal Thermal Climate Index (UTCI), Potential Air Temperature (PotAT) – height 1,5 m.



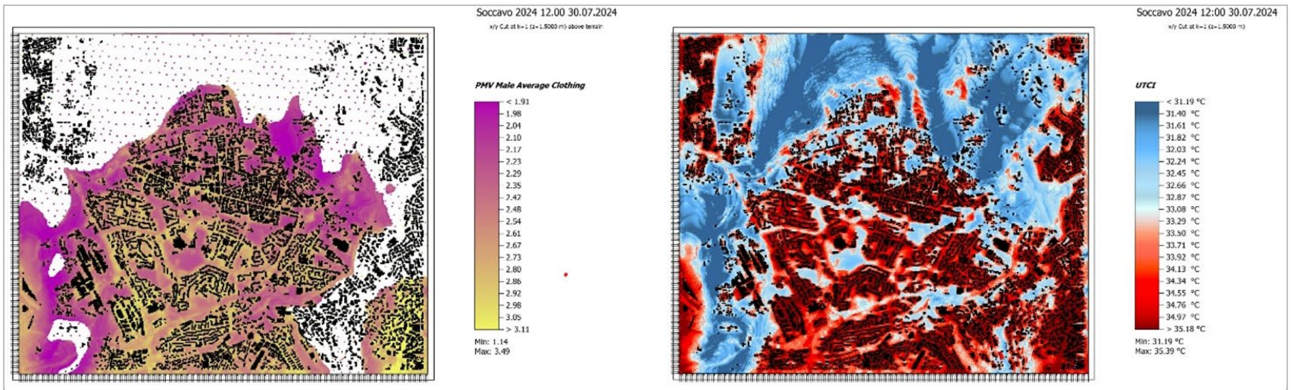


Figure 16. Extract of data from ENVI-met simulations for the ex ante scenario

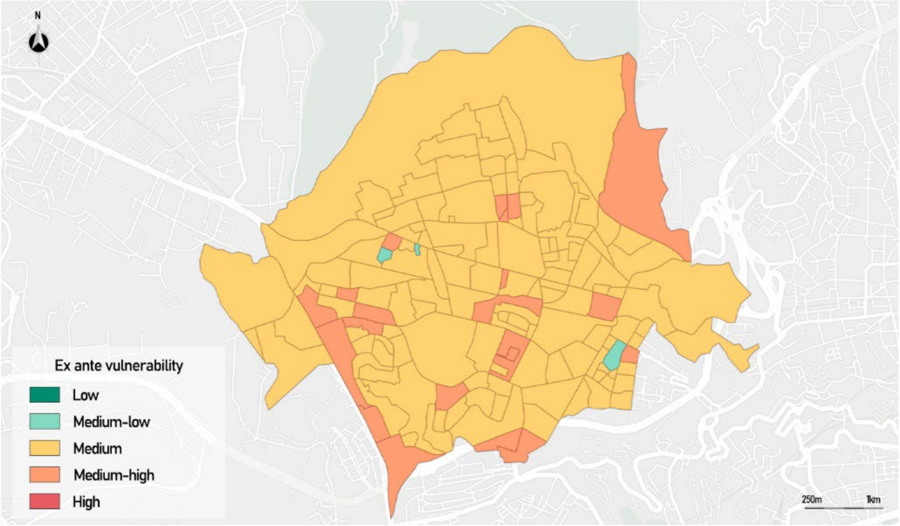


Figure 17. Ex-ante heatwave vulnerability

SCENARIO POST

The ex-post scenario assumes the implementation of cool islands in the Soccavo district. Cool Islands are urban or peri-urban areas that offer cooler temperatures than the rest of the surrounding city to mitigate the effects of urban heat islands. For the district, they are identified based on a series of criteria, parameters, and indicators. They are then overlaid with potentially transformable green areas based on the PRU and PRG, and those that intersect are identified as areas for intervention based on a 15-minute walking buffer.

To this end, the what-if scenario is developed assuming the application of strategies implementing climate-proof interventions and aligned with the Italian National Climate Change Adaptation Plan (PNACC). These actions aim to mitigate heatwave vulnerability by enhancing urban greenery and integrating "cool islands" within both existing and planned park infrastructures.

METRICS POST

The metrics for the assessment of the ex-post scenario are the same as those used for the ex-ante one, so as to enable an easy comparison between the two.

The comparison between the simulation data of the ex ante and ex post scenario shows a significant change in Sky View Factor. Comparing the ex-ante and ex-post maps, a reduction in SVF values emerges in areas affected by urban reforestation and in new green spaces. The decrease in SVF implies a reduction in direct exposure to the sky and solar radiation, a condition associated with an improvement in average thermal conditions and the containment of radiant temperature during the central hours of the day. The Shadow Hours Analysis also shows consistent results. The ex-post scenario shows an increase in surfaces receiving more than 6–8 hours of daily shade, while the areas remaining almost completely exposed (0–2 hours) significantly decrease compared to the ex-ante scenario. This result directly reflects the presence of new trees and the expansion of the planned green areas.

Mean Radiant Temperature (MRT), one of the indicators most affected by the presence of shading, shows a reduction in its maximum value from approximately 63.35°C in the ex-ante scenario to 60.48°C in the ex-post scenario. This approximately 3°C decrease in peak values is a tangible effect of the increase in shading, confirming the ability of new green infrastructure to attenuate incident radiation.

PET (Physiological Equivalent Temperature) shows similar maximum values between the ex-ante and ex-post scenarios in all categories (children, adults, elderly), with differences of a few tens of tenths of a degree. However, the spatial distribution of values has changed: in the intervention areas, the areas belonging to the moderate classes (32–38°C) have increased, while the areas with high values (>44°C) have decreased. This indicates a widespread improvement, despite unchanged maximum peaks, which are more affected by the atmospheric conditions input to the model rather than by local interventions.

The Predicted Mean Vote (PMV) shows a more significant improvement. In the ex-post scenario, the minimum PMV value for each category is lower than the ex-ante scenario (for example, 1.22 versus 1.90 for children), and there is an expansion of areas with lower PMV in the treated zones. This suggests a real improvement in perceived thermal comfort, thanks to the reduction in radiation and the increase in local ventilation favored by the presence of green spaces.

The Predicted Percentage of Dissatisfied (PPD) confirms this trend: in the ex-post scenario, an increase in areas with dissatisfaction scores between 30% and 60% is observed to the detriment of the higher categories (>90%) that were widespread in the ex-ante scenario (pp. 12-15). The presence of new areas with minimum PPD (10–20%) in green areas represents a significant improvement in comfort.

The Potential Air Temperature (PotAT) recorded at 1.5 m above ground shows a slight decrease in its maximum value, going from 32.24 °C in the ex-ante scenario to 31.71 °C in the ex-post scenario. Although the numerical difference appears small (about 0.5 °C), the map analysis shows a greater extension of surfaces belonging to the cooler classes (27.6–29.5 °C), indicative of a localized microclimatic improvement.

Regarding relative humidity, the ex-ante scenario shows values between 48% and 83%, while a direct map is not available in the ex-post scenario. However, based on microclimatic principles and the significant increase in plant biomass, it is reasonable to expect a localized increase in relative humidity between 2% and 5%, especially in densely wooded areas and parks.

Finally, the green areas produce a local reduction in UTCI between −0.7 and −1.5°C, with more pronounced effects in parks and cool islands, and more continuous along tree-lined corridors. These results confirm that increased shade, reduced SVF, and increased evapotranspiration generate measurable cooling, consistent with the scientific literature on nature-based solutions in urban environments.

Overall, the combined spatial and quantitative analysis confirms that climate-proof actions are most effective in reducing *Medium–high* vulnerability conditions, while highlighting the need for broader, more integrated strategies to achieve substantial vulnerability reduction across the extensive medium-vulnerability fabric.

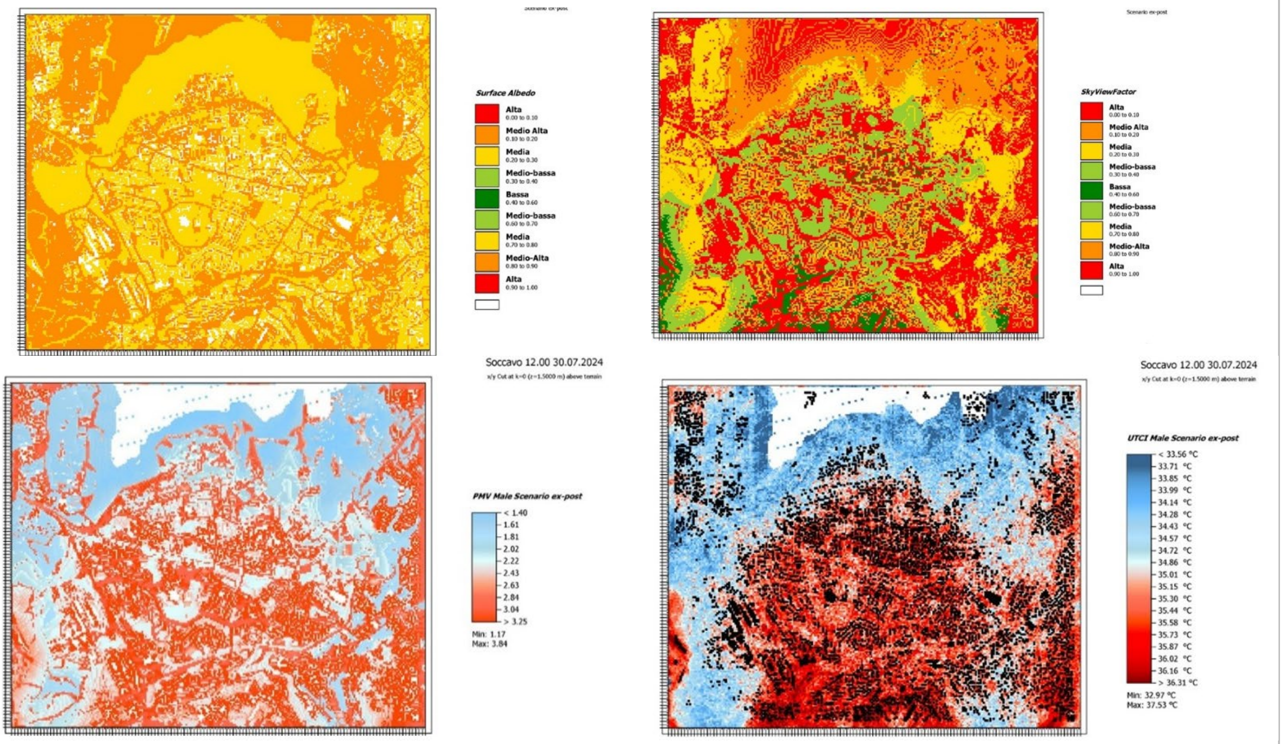


Figure 18. Extract of data from ENVI-met simulations for the ex post scenario

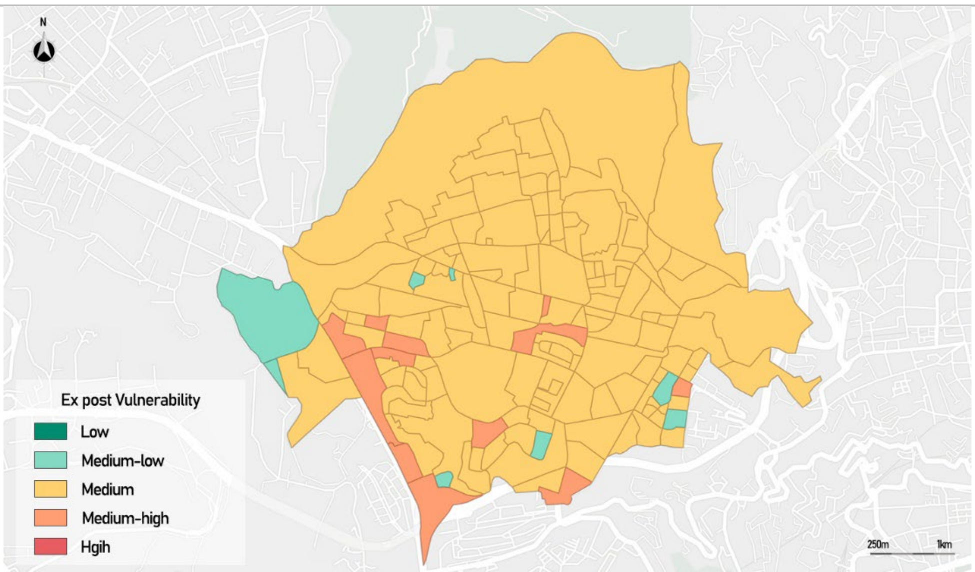


Figure 19. Ex-post heatwave vulnerability

TOOLS

× ESRI ArcGIS Pro 3.5	× ENVI-met	☐ …		

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4.3. A multifactorial holistic indicator for the monetization of natural capital (VCU) as a multiplier of social added value and relational goods

WHAT-IF SCENARIOS CASE STUDY COLLECTION
measuring the effect of multi-risk mitigation and adaptation

A multifactorial holistic indicator for the monetization of natural capital (VCU) as a multiplier of social added value and relational goods: a method, rather than a model, of SROI integrating CBA. Climate Resilience as a Relational Common: deconstructing the cost of inaction through Integrated Nature-Based Solutions in Soccavo, Naples.

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TASK RETURN

Task 5.5.3 - The resilient-city simulation test of mitigation and adaptation scenarios

RESEARCH OBJECTIVES

This paper defines a methodological framework for the construction of a multifactorial holistic indicator designed to monetize Natural Capital within the urban fabric of the Soccavo district. The primary research objective is the implementation of an integrated Cost-Benefit Analysis (CBA) enhanced by a social-relational SROI (Social Return on Investment) approach, capable of quantifying the impact of Nature-Based Solutions (NBS) under multi-hazard scenarios (specifically urban heat islands and pluvial flooding). By accounting for environmental externalities and social added value, the study aims to provide decision-makers with a robust tool to evaluate "what-if" scenarios, moving beyond traditional market-driven logic to address thermal inequality and the systemic costs of climate inaction.

KEYWORDS

Multifactorial Holistic Indicator, Natural Capital Monetization, Multi-hazard Resilient Planning, Climate Inaction Cost-Opportunity

SCALE

☐ territorial	X macro-district	☐ district	☐ census zone		

URBAN CONTEXT

☐ city centre	☐ historic centre	☐ industrial area	☐ periurban area	X periphery neighborhood	

RISK MITIGATED

X heatwave	X Pluvial flooding	☐ Seismic	☐ …		

SCENARIO ANTE

The *ex ante* scenario for the Soccavo district (Municipality 9) constitutes a state of climate inaction that generates a profound socio-economic debt. This condition is not a neutral baseline but a regressive trajectory where the absence of Nature-Based Solutions (NBS) exacerbates the synergistic risks of Urban Heat Islands (UHI) and pluvial flooding (Runoff). By moving beyond the reductionist logic of the *lex mercatoria*, this work integrates ethical imperatives with a multifactorial holistic methodology to quantify the systemic "cost of doing nothing."

Traditional Cost-Benefit Analysis (CBA) often suffers from a reductionist bias, operating within the limits of a market-driven logic that quantifies only what is commercially exchangeable. This research moves beyond such constraints by integrating the ethical critiques of contemporary thought:

- The Corruption of Goods (Sandel, 2012): Market reasoning, when applied to non-market goods such as public health or urban ecosystems, risks "corrupting" their intrinsic value. To counter this, urban greenery is redefined as a Relational Common—a shared asset whose utility lies not in its physical presence alone, but in its capacity to enable social interaction and collective well-being.;
- The Capabilities Approach (Nussbaum, 2011): Welfare should not be reduced to a mere monetary figure. According to Martha Nussbaum, the state must guarantee fundamental "capabilities," including life and bodily health. In Soccavo, climate inaction violates these capabilities by denying citizens a safe environment, thereby necessitating a shift toward the Multifactorial Holistic Indicator;

The integration of Social Return on Investment (SROI) (Yates & Marra, 2017) within the CBA framework responds to the need to quantify social and relational value. Unlike traditional methods, SROI measures change by engaging stakeholders and monetizing externalities that the market ignores.

The Economic Deprivation Multiplier: in the current inertial state, the lack of NBS results in a measurable Economic Deprivation Multiplier. This figure represents the systemic loss of social capital and "relational goods" that the community suffers due to environmental degradation and social isolation.

Global Benchmarks: this approach aligns with international literature, such as the Visionary NBS project (Vasiliu et al., 2024), which demonstrates how SROI can account for intangible benefits like stress reduction and social cohesion in Italian urban green spaces. Similarly, the work of Tiwary et al. (2016) confirms that mitigating UHI and Runoff must be evaluated through a performance-based multifactorial index.

The data regarding the inertial state in Soccavo transforms abstract climate risks into harrowing statistical certainties. The failure to intervene results in:

- Avoidable Mortality: the model estimates a total of 477.18 fatalities (Vite perse M9 ex ante) directly attributable to heatwaves. By accounting for the "Value of a Statistical Life," it becomes clear that maintaining the *status quo* is a decision to accept predictable fatalities;
- Systemic Healthcare Pressure: thermal peaks, projected to reach an anomaly of +3.49°C by 2025, drive systemic healthcare costs. Each hospitalization for heatstroke incurs an average direct cost of €631.60. Furthermore, the model accounts for critical care demands, with average Intensive Care Unit (ICU) stays of 3.4 days;
- Thermal Inequality (Vasiliu et al., 2024): this indicator highlights how climate inaction disproportionately affects low-income residents who lack the private means to adapt, turning the UHI effect into a driver of social divergence;

The environmental cost of inaction is further quantified through the Runoff Coefficient. In the high-density, impermeable fabric of Soccavo, the persistence of a high coefficient leads to recurring structural damage from "water bombs" and extreme precipitation. The financial burden of emergency maintenance and infrastructure repair represents a passive drain on public resources that exceeds the capital expenditure required for transformative sustainable drainage systems.

The synthesis of multifactorial data confirms that the inertial scenario is the most expensive option for the decision-maker. By accounting for the savings in healthcare expenditure and the monetization of relational commons, the model proves that "non-action" is a choice that consumes human, social, and financial capital. The transition toward a resilient urban model is therefore not a discretionary expense, but a mandatory investment to halt the ongoing socio-climatic hemorrhage of the Soccavo district.

METRICS ANTE

The *ex ante* scenario is not merely a data-driven baseline; it is a systematic accumulation of liabilities. The adopted metric departs from traditional Cost-Benefit Analysis (CBA) to embrace a holistic vision where decision-making inaction is treated as a direct loss of human and social capital.

The formula is built upon objective demographic and climatic data that define the risk perimeter for Municipality 9 (M9):

- M9 Population Percentage (0.04693): the demographic weight of the district relative to the city's total population;
- Projected Thermal Anomaly (+3.49°C): the heat peak forecasted for 2025, acting as a risk multiplier in a scenario devoid of Nature-Based Solutions (NBS);
- Runoff Coefficient (C): in the *ex ante* scenario, this index is at its maximum, indicating that nearly all precipitation is converted into surface runoff, leading to inevitable infrastructure damage;

The formula integrates the raw costs of "doing nothing," translating the ethical critiques of Sandel (2012) and Nussbaum (2011) into numerical variables:

- M9 Lost Lives: this represents the estimated excess mortality. Here, the metric rejects the *lex mercatoria* logic of pure market exchange, utilizing the "Value of a Statistical Life" (VSL) to demonstrate the ethical unsustainability of inaction;
- Hospitalization Cost and Intensive Care Unit Stay: these indicators measure the direct economic pressure on the National Health Service caused by the Urban Heat Island (UHI) effect;
- Morbidity and Productivity Loss: An indicator quantifying psychophysical distress and lost workdays, further burdening the district's economic balance.

The Economic Deprivation Multiplier acts as a "penalty rate" for the *ex ante* scenario:

- It represents the total absence of Relational Goods and Social Capital;
- I utilize this value to monetize what the community "loses" in terms of mental health and social cohesion by lacking access to a Relational Common (urban public greenery);

In the *ex ante* scenario, the Holistic Indicator is ideally zero (no risk reduction), which causes the negative SROI (Social Return on Investment) costs to soar.

Through this metric, I demonstrate that a decision-maker choosing the inertial scenario is implicitly approving a hidden and devastating public expenditure. Thermal Inequality (Vasiliu et al., 2024) is not just a sociological concept but a mathematical reality: in Soccavo, inaction costs 477 lives and millions of euros in negative externalities. In conclusion, the *ex ante* metric transforms the "void" of non-intervention into a ledger of debts. By using integrative SROI, it is proven that climate resilience is not an optional cost, but the only way to settle the debt owed to the health and dignity of the citizens of Municipality 9.

SCENARIO POST

The transition from the inertial state to the project phase is not uniform. The formula disaggregates impacts into three distinct scenarios, each modifying the Holistic Reduction Indicator and the Social Return on Investment (SROI) through different combinations of physical and economic variables.

The "Reforestation" Scenario prioritizes the biological component to maximize thermal mitigation.

- Technical Parameters: the intervention involves the planting of approximately 1,750 large-canopy trees (e.g., *Platanus acerifolia*, *Quercus ilex*). These species are selected for their high leaf area index (LAI) and evapotranspiration rates;
- Economic Variables: the estimated CAPEX is €4,795,000. This investment focuses exclusively on green procurement, planting, and specialized maintenance;

This is the most effective strategy for reducing surface temperature. It directly addresses the 477.18 avoidable deaths identified in the *ex ante* scenario. By creating "Relational Commons" (Sandel, 2012), it restores the fundamental "capability" of bodily health (Nussbaum, 2011).

The Blue-Green Infrastructure and Hydraulic Safety Scenario focuses on permeable surfaces and sustainable drainage systems (e.g., rain gardens, bioswales, and porous pavements).

- Technical Parameters: the focus shifts from tree count to the square footage of de-sealed soil. The primary goal is the reduction of the Runoff Coefficient;

- Economic Variables: the costs are driven by civil engineering and specialized permeable materials. While the initial investment is high, it yields immediate returns by eliminating the costs of infrastructure repair and emergency sewage maintenance.

This scenario excels in hydraulic resilience, protecting Municipality 9 from the financial and physical damages of "water bombs." It satisfies the requirement for physical security but has a more limited impact on extreme heat compared to dense reforestation.

The Holistic Optimization Scenario represents the perfect synthesis and the point of maximum efficiency in the multifactorial formula.

- Synergy of Parameters: the Integrated Scenario combines the 1,750 trees with structural NBS. It is the only configuration that achieves the maximum value for the Holistic Indicator, addressing both heatwaves and flooding simultaneously.
- SROI Maximization: by totally neutralizing the Economic Deprivation Multiplier (1.6466) and restoring the Natural Capital Value (NCV), this scenario proves that the aggregate social benefit far exceeds the sum of the individual parts.

The following table summarizes the comparative performance of the scenarios against the Ex Ante (Inertial) state.

Indicator	**Ex Ante (Inaction)**	**Reforestation**	**NBS (Technical)**	**Integrated Scenario**
Avoidable Deaths (M9)	477.18	~65% Reduction	~30% Reduction	>85% Reduction
Healthcare Costs (NHS)	Maximum (€631.60/ev)	High Savings	Moderate Savings	Maximum Savings
Runoff Damage	Constant Liability	Moderate	Minimum	Minimum
Social Return (SROI)	Negative	High	Medium-High	Optimal

The final decision is guided by the ethical imperative to maximize saved lives while ensuring economic efficiency:

- Life-Saving Priority: although the Integrated Scenario requires the highest CAPEX, it offers the greatest reduction in mortality. When the Value of a Statistical Life (VSL) is applied, the "cost" of the project is entirely offset by the economic value of the lives saved and the prevention of 3.4-day ICU stays for heat-related illnesses;
- Elimination of Thermal Inequality: only the Integrated Scenario provides a systemic response to Thermal Inequality (Vasiliu et al., 2024), protecting the most vulnerable citizens of Soccavo from both thermal and hydraulic risks;

Economic Repair: inaction is the most expensive "choice." The Integrated Scenario is not a discretionary expense; it is an act of economic reparation that settles the debt incurred by the district's current state of neglect. In conclusion, the holistic metric proves that the Integrated Scenario is the only rational choice. It transforms the "silent tragedy" of avoidable deaths into a quantifiable gain in human capital, proving that urban resilience is the highest form of public spending efficiency.

METRICS POST

Naples is characterized by an extreme degree of soil sealing and high population density, creating a "thermal and hydraulic trap." In the Ex Ante scenario, the city lacks adaptive infrastructure, leading to what I define as a state of Climate Inaction.

Metric of Inaction: The inertial state is not "cost-free." It is a ledger of missing benefits and opportunity costs. The formula identifies 477.18 avoidable deaths in M9, driven by a projected thermal anomaly of +3.49°C. Every euro "saved" by not intervening is actually a multi-euro debt incurred through healthcare strain (ICU stays of 3.4 days) and loss of human capabilities (Nussbaum, 2011).

The project phase is divided into three levels of intervention, moving from biological mitigation to integrated engineering.

Scenario 1: Urban Reforestation (Natural Capital)

- Technical Details: Planting of 1,750 large-canopy trees (e.g., *Platanus*, *Tilia*). Total Cost (CAPEX): €4,795,000;
- Incremental Benefits: This scenario is the most efficient in terms of reduction. It addresses the mortality rate directly. However, it offers limited protection against extreme runoff events as the ground remains largely impermeable.

Scenario 2: Bioretention Cells and Blue-Green NBS

- Technical Details: implementation of Bioretention Cells and bioswales. These are engineered depressions designed to capture, treat, and infiltrate stormwater. Total Cost (CAPEX): €6,250,000.
- Incremental Benefits: unlike simple planting, Bioretention Cells drastically lower the Runoff Coefficient. This scenario prevents infrastructure damage and "water bomb" disasters, fulfilling the capability of "physical security."

Scenario 3: Integrated Strategic Intervention (Reforestation + NBS)

- Technical Details: A synergistic fusion of 1,750 trees and structural Bioretention Cells. Total Cost (CAPEX): €11,045,000;
- Incremental Benefits: This represents the maximum value for the Holistic Reduction Indicator (R). It is the only scenario that simultaneously solves the "silent tragedy" of heat deaths and the economic drain of flooding.

To determine the preferable scenario, I apply the Social Return on Investment (SROI) metric, which monetizes the avoided costs of the *Ex Ante* state.

Indicator	**Ex Ante (Inaction)**	**Scenario 1 (Trees)**	**Scenario 2 (Bioretention)**	**Scenario 3 (Integrated)**
Total Investment (CAPEX)	€0	€4,795,000	€6,250,000	€11,045,000
Avoided Mortality (Lives)	0 (Liability)	~310 lives saved	~143 lives saved	>405 lives saved
Healthcare Savings (NHS)	€0 (Debt)	High	Medium	Maximum
Hydraulic Risk Mitigation	0%	Low	High	Total
Relational Value Gain	-1.6466 (Loss)	Positive	Moderate	Maximum
SROI Outcome	Negative	Positive (Low-Med)	Positive (Med)	Optimal (Highest)

The metric proves that Scenario 3 (Integrated) is the only rational choice for the decision-maker. While it requires the highest initial expenditure, it yields the highest SROI. By choosing to invest €11.04M, we are not merely "spending"; we are repairing the economic and human deficit of the inertial state. The Integrated Scenario settles the debt of 477 avoidable deaths and the 1.646 multiplier of social deprivation. In light of the Value of a Statistical Life (VSL), the Integrated Scenario is the only one that fully transforms the Soccavo district from a site of climate inequality into a resilient Relational Common.

TOOLS

☐ GIS Suite ESRI ArcGIS Pro	X Excel	☐ …		

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4.4.Climatic and geophysical risks in urban areas. A testing in Bagnoli, Naples.

WHAT-IF SCENARIOS CASE STUDY COLLECTION

measuring the effect of multi-risk mitigation and adaptation

Climatic and geophysical risks in urban areas. A testing in Bagnoli, Naples

M.F. Leone, M.T. Girardi, A. Pallotta

RESEARCH UNIT

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2. Centro Studi PLINIVS-LUPT
3. Urban Climate Change Research Network European Hub

TASK RETURN

VS3 - Task 7.2 - Dynamic Multi-Risk Maps for Multi-objective Strategies (UNINA)

RESEARCH OBJECTIVES

The aim of this research is to develop an integrated multi-hazard assessment framework addressing both geophysical and climate related hazards, to evaluate the effectiveness of combined urban design interventions in reducing overall multi-risk conditions. The methodology supports the analysis of impact scenarios, both ex-ante and ex-post, quantifying how interventions on buildings and open spaces can reduce the impact of heat waves, pluvial flooding, earthquakes, and volcanic ashfall. What-if scenarios are explored to assess the potential of multi-risk strategies to enhance urban resilience, guide priority interventions, and balance everyday urban functions with emergency preparedness in the Bagnoli district of Naples.

KEYWORDS

multi-hazard assessment, urban resilience, climate adaptation, seismic and volcanic risk, impact assessment

SCALE

☐ territorial	☐ macro-district	**X** district	☐ census zone		

URBAN CONTEXT

☐ city center	☐ historic center	**X** industrial area	☐ periurban area	**X** periphery neighbourhood	

RISK MITIGATED

X heatwave	**X** pluvial flooding	**X** seismic	**X** volcanic		

SCENARIO ANTE

CLIMATIC IMPACTS

The ex-ante climate impact scenario constitutes an assessment developed in alignment with the most recent international frameworks for climate risk and resilience analysis, as articulated in the IPCC Sixth Assessment Report (AR6, 2022). The scenario is constructed through the integrated modelling of climatic hazards, exposure, and vulnerability, with the objective of identifying the impacts on selected elements at risk (population for heat waves, buildings and infrastructure for pluvial flood) under projected future climate conditions.

To support this assessment, three dedicated modelling tools were developed: (i) a model for the simulation of heatwave events and the assessment of urban thermal stress, (ii) a model for the simulation of energy consumption, and (iii) a model for the evaluation of pluvial flooding and associated urban impacts. The methodological approach builds on modelling techniques consolidated through recent European research initiatives (e.g. Horizon Europe KNOWING, UP2030, ICARIA projects), which have advanced the capacity to simulate climate-related impacts at the urban scale.

The scenario combines historical climate data for the reference period 1985-2014 with projections of event frequency up to 2070, assessed under two widely used and plausible global emission pathways: SSP5-8.5, representing the continuation of current high-emission trends, and SSP2-4.5, reflecting a pathway of moderate emission reductions. Together, these analyses provide a consistent and robust framework for evaluating the potential effectiveness and prioritization of future mitigation and adaptation measures in response to anticipated climate impacts.

Climatic impacts are quantified in economic terms. For heatwaves, impacts are assessed through estimated hospitalization costs associated with heat-related illnesses. For pluvial flooding, impacts include the costs of road cleaning and restoration, as well as economic losses related to structural damage and damage to building contents.

The three modeling tools are:

- **Heatwave: HWLEM Model (PLINIVS-LUPT Study Center)**
  The HWLEM (Heat Wave Local Effect Model) analyses urban heat island conditions and both outdoor and indoor thermal comfort by combining geospatial data, digital terrain models, and advanced computational algorithms. It adopts a 2.5D approach that integrates two-dimensional land-use data with three-dimensional information such as elevation, shading, and Sky View Factor.
  The model's main inputs include detailed land-cover maps, specific values of albedo, emissivity, and surface temperature, as well as shading information from built structures and vegetation, evaluated through a Digital Surface Model (DSM). HWLEM allows for the estimation of how resilience measures in open spaces can reduce exposure and improve urban thermal comfort.

- **Energy Consumption Model (PLINIVS-LUPT Study Center)**
  The Energy Consumption Model estimates the energy demand per m2 of buildings by adopting a typology-based approach that links construction characteristics to use-related performance parameters. The calculation framework is based on a set of coefficients derived from key building attributes. Energy demand is first determined by the building use, to which specific coefficients are assigned to represent the contribution of building systems (HVAC and technical installations). Additional coefficients account for internal thermal loads associated with different use categories. The model then incorporates envelope-related factors, including the Window-to-Wall Ratio (WWR) and the surface-to-volume ratio, which captures the geometric efficiency of the building. Finally, the contribution of the building envelope is refined based on construction typology – distinguishing between masonry and reinforced concrete structures – and construction period, allowing the model to reflect variations in thermal performance linked to historical building practices.

- **Pluvial Flooding: SFINCS Model (Deltares)**
  SFINCS (Super-Fast INundation of CoastS) is an impact assessment model specifically developed to address the challenges of compound flooding. It integrates inputs from climate, ocean, and hydrological models—such as precipitation, sea levels, and river discharge—to simulate flood events, making it suitable for representing climate change impacts.
  It is particularly well-suited for simulating individual extreme events over short timescales of a few days. In addition to natural drivers, the model accounts for urban infrastructure and planned adaptation measures, ranging from dikes and green spaces to interventions that enhance the infiltration capacity of urban soils.

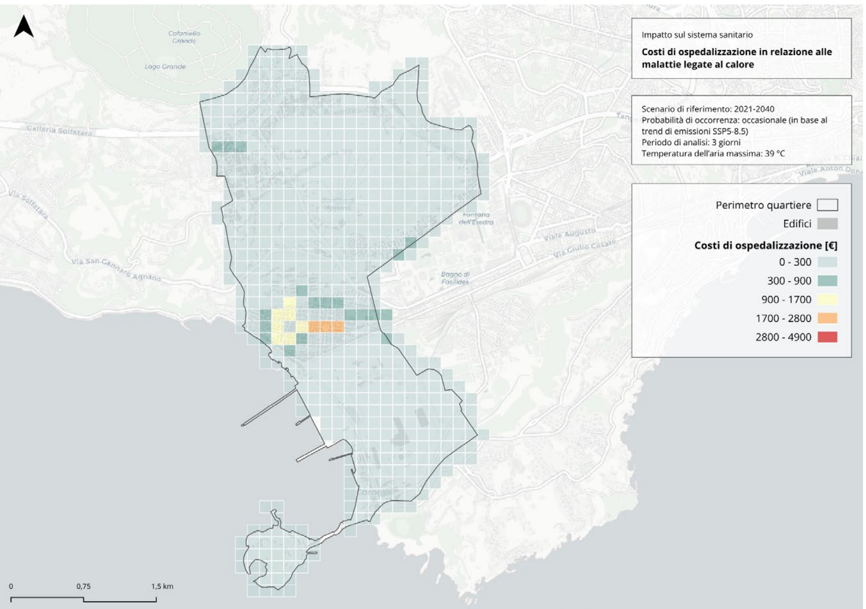

Figure 20. Estimated hospitalization costs linked to illnesses triggered by thermal stress conditions, referring to a heat-wave event with an air-temperature peak of 39 °C lasting 3 days, classified as having an "occasional" likelihood of occurrence in the period 2041–2070 under the SSP5-8.5 emission scenario. The map illustrates the situation as of November 2024

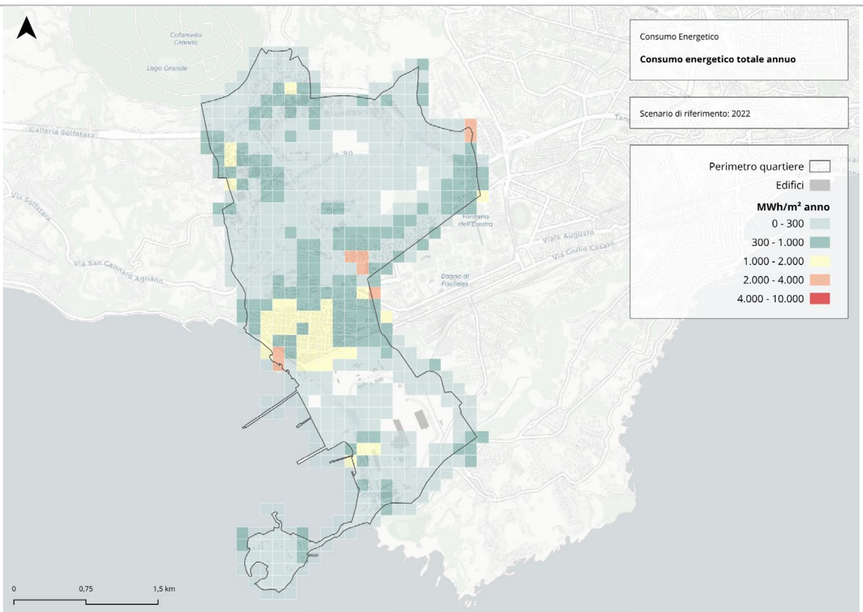

Figure 21. . Energy consumption of buildings for the year 2022

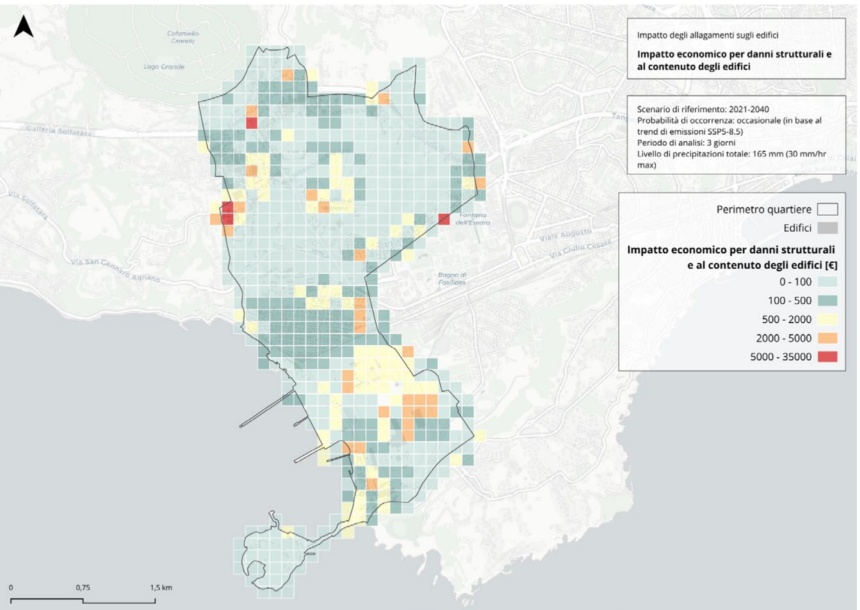

Figure 22. Economic impact due to structural and content damage to buildings resulting from a rainfall event of 165 mm over 3 days, with a peak intensity of 30 mm/hr, corresponding to an "occasional" scenario in the 2021–2040 period and a "frequent" one in the 2041–2070 period, based on the SSP5-8.5 emissions pathway

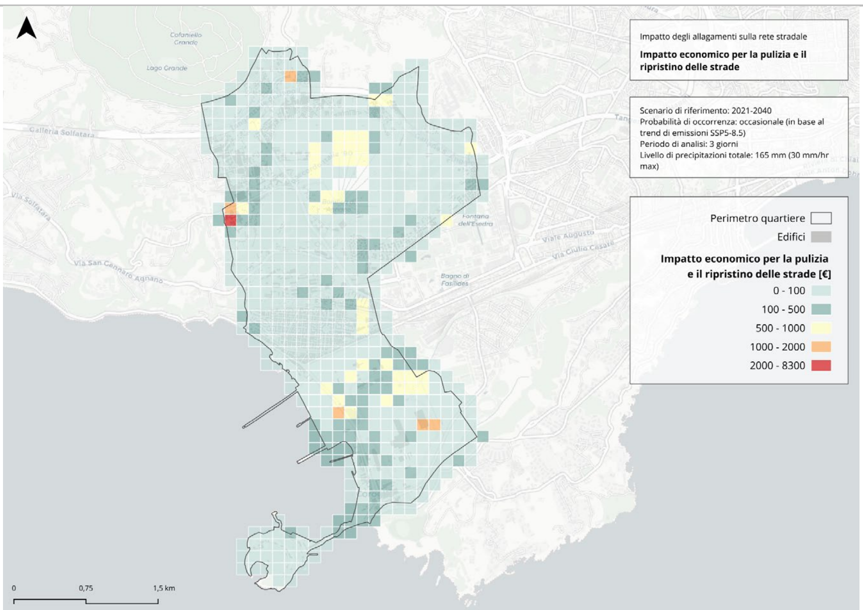

Figure 23. Economic impact of street cleaning and restoration following surface flooding events, associated with a rainfall event of 165 mm over 3 days, with a peak intensity of 30 mm/hr, corresponding to an "occasional" scenario for the period 2021–2040 and a "frequent" scenario for the period 2041–2070, based on the SSP5-8.5 emissions pathway.

GEOPHYSICAL IMPACTS

The ex-ante geophysical impact scenario is assessed in relation to the population and infrastructure exposed to seismic and volcanic hazards. Hazard characterization is based on historically documented events, whose recorded intensities are adopted as reference conditions for the scenario. These observed events also provide spatially explicit damage data, enabling a direct correlation between hazard intensity and the spatial distribution of exposed elements.

A dedicated seismic assessment methodology—S.A.V.E. (Seismic Assessment for Vulnerability Expectation)—is employed to support the characterization of seismic exposure and vulnerability. Exposure and vulnerability are jointly defined through the assignment of vulnerability classes to the systems under analysis, namely buildings and population, and through the derivation of vulnerability curves that describe expected levels of damage as a function of hazard intensity.

Through the integration of hazard, exposure, and vulnerability components, the model enables the simulation of geophysical impacts. These impacts are quantified in terms of expected building losses due to seismic events, roof collapses induced by volcanic ash fall, and the resulting number of displaced residents.

- **S.A.V.E. (Seismic Assessment for Vulnerability Expectation)** is an empirical procedure designed to estimate and classify building performance based on typological data, damage levels, and seismic hazard intensity. S.A.V.E. integrates both vulnerability and exposure, using the relationships between collected information to construct a fragility/vulnerability classification. By leveraging typological data and damage databases, the model quantifies the spatial distribution of vulnerability across the study area, providing an estimate of the expected impact on individual buildings.

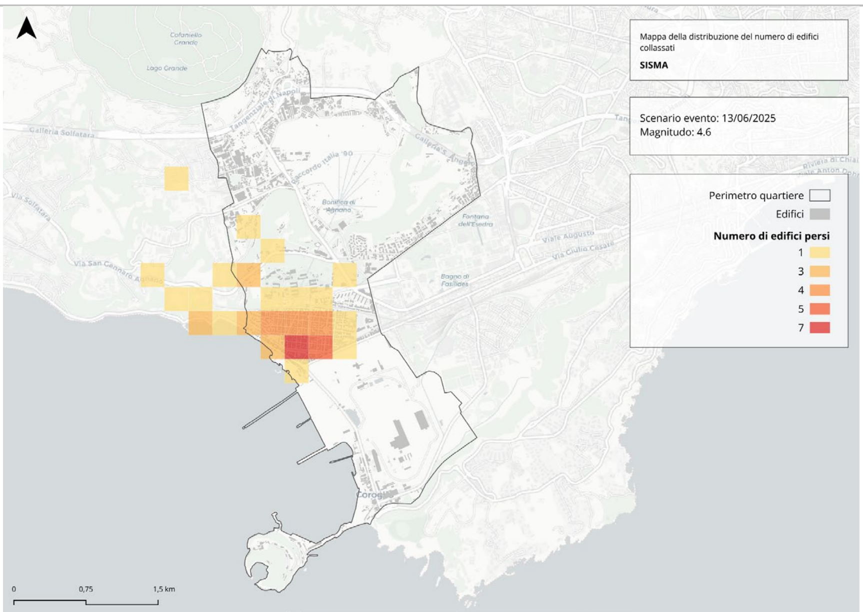

Figure 24. Estimated distribution of collapsed buildings resulting from a magnitude 4.6 earthquake that occurred on 13 June 2025. The map illustrates the situation as of June 2025

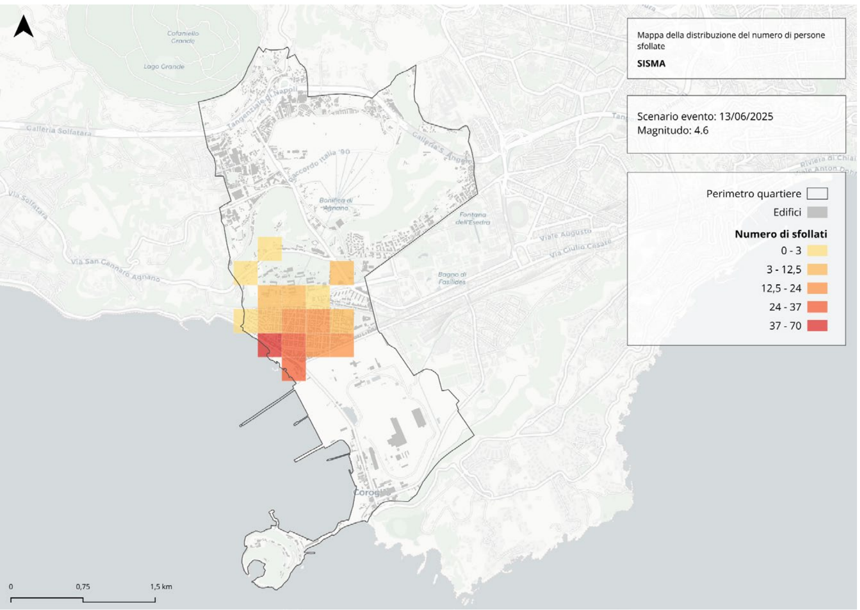

Figure 25. Estimated distribution of displaced residents resulting from a magnitude 4.6 earthquake that occurred on 13 June 2025. The map illustrates the situation as of June 2025

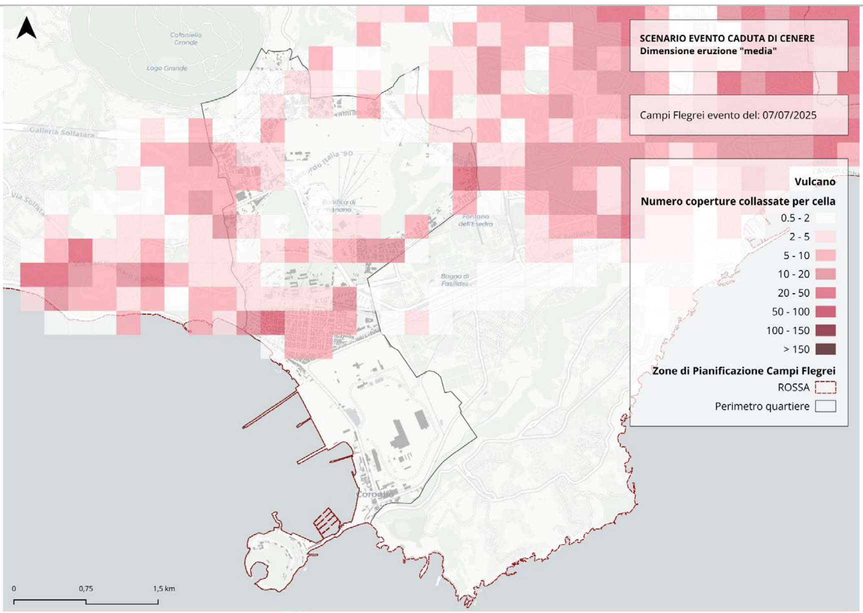

Figure 26. Estimated number of roof collapses caused by ash fallout from a medium-size eruptive event at the Campi Flegrei volcanic area on 07 July 2025. The map illustrates the resulting impacts on building structures across the affected area

SYNTHETIC IMPACT

The ex-ante impact scenario provides an integrated and coherent assessment of the main climatic and geophysical risks at the urban scale, enabling the identification of the most exposed and vulnerable elements under both current and future conditions. By integrating historical data with projections up to 2070, the scenario delivers quantitative estimates of expected impacts under different emission pathways, supporting scenario comparison, and the prioritization of intervention strategies.

The results include the quantification of climate-related impacts in terms of healthcare costs associated with heatwave-related illnesses and economic losses linked to pluvial flooding, as well as the estimation of geophysical impacts expressed as expected losses to the building stock, damages induced by seismic and volcanic events, and the number of potentially displaced residents. Overall, the ex-ante scenario provides an operational knowledge base to guide mitigation and adaptation strategies, assess their potential effectiveness, and strengthen decision-making processes in the field of climate resilient urban development (IPCC, 2022).

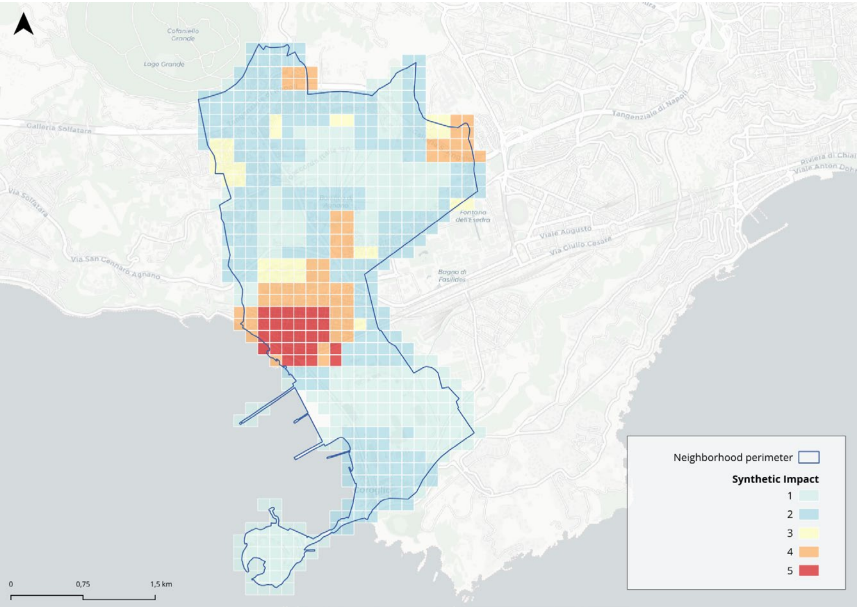

Figure 27. Synthetic impact map of the ex-ante scenario for the Bagnoli district. This map provides an integrated assessment of climatic and geophysical impacts at the urban scale, highlighting the most exposed and vulnerable elements under current conditions. It combines estimates of healthcare costs from

heatwaves, economic losses from pluvial flooding, and expected building damages and displacement resulting from seismic and volcanic events, offering a comprehensive overview to support prioritization of multi-risk interventions and climate-resilient urban planning.

METRICS ANTE

CLIMATIC HAZARDS

Within this framework, climatic hazards are characterized through indicators that capture their intensity, frequency, and spatial distribution, ensuring consistency with the broader structure adopted for the impact scenario. For heatwaves, two complementary indicators are employed. The Mean Radiant Temperature (MRT) reflects outdoor thermal stress by integrating air temperature, surface temperatures, urban morphology, and the radiative properties of built and open spaces. Indoor conditions are instead represented through the annual energy consumption per unit of floor area, which serves as a proxy for the energy required to maintain acceptable indoor comfort levels under extreme heat; this indicator captures how building characteristics and climatic conditions jointly influence heat-related vulnerability. Rainfall-induced flooding is described through the probability of inundation, defined on the basis of hydrological and geomorphological variables. In particular, the indicator depends on surface runoff coefficients—which express the area's capacity to retain or convey rainfall—and on the morphology of local drainage basins, which determines the concentration and routing of surface waters during intense precipitation events.

GEOPHYSICAL HAZARDS

Similarly, geophysical hazards are characterized through specific indicators that describe the potential intensity and spatial manifestation of seismic and volcanic events, ensuring consistency with the overall framework adopted in the impact analysis. For earthquakes, the seismic hazard is represented using macroseismic intensities, which provide an integrated measure of ground shaking as experienced across the built environment. This indicator captures the severity of shaking at the local scale and its capacity to produce structural damage, forming the basis for linking observed historical events with the vulnerability of buildings and population.

Volcanic hazard is described through two complementary parameters reflecting the dominant destructive processes associated with explosive eruptions. The dynamic pressure of pyroclastic flows quantifies the mechanical impact exerted by high-velocity, high-density pyroclastic currents on exposed structures, providing a measure of their potential to cause partial or total collapse. The ash-fall load, instead, represents the static weight accumulated on building roofs and open surfaces, which constitutes the primary driver of structural overstress and collapse during fallout events. Together, these indicators capture the range of physical stresses that volcanic phenomena can impose on the urban system.

VULNERABILITY

Vulnerability is defined as the intrinsic propensity of exposed elements to suffer damage when subjected to a given intensity of climatic or geophysical hazard. Following the IPCC framework (2014; 2022) and consolidated methodologies in impact modelling, vulnerability is treated as a damage function, expressing the probability that an element belonging to a specific vulnerability class will experience a given level of loss under a defined hazard intensity. Its construction requires first the identification of exposed systems and their organization into homogeneous classes based on physical, environmental, and socio-economic characteristics. In this integrated assessment, vulnerability is evaluated across the three systems potentially compromised by both climate-related and geophysical events: buildings, people, and open spaces.

For buildings, vulnerability reflects their physical susceptibility to structural damage and is described through three indicators, each corresponding to a specific hazard: the seismic vulnerability class, the vulnerability class to pyroclastic flows, and the vulnerability class to ash-fall load. These indicators capture the capacity of the building stock to resist shaking, dynamic pressure, or vertical loading, and form the basis for estimating expected structural losses. For open spaces, vulnerability relates to their environmental sensitivity and their ability to mitigate or exacerbate climate impacts. It is described through the Normalized Difference Vegetation Index (NDVI), which expresses vegetative health and shading potential; the Land Surface Temperature (LST), which reflects the thermal behaviour of urban surfaces during heat stress; and the infiltration capacity of urban soils, which determines the susceptibility of surfaces to accumulate runoff during heavy rainfall.

For people, vulnerability incorporates social and physiological sensitivity to both climatic and geophysical hazards. It is represented through the Universal Thermal Climate Index (UTCI), a measure of outdoor heat stress; energy poverty, which reflects the capacity of households to maintain adequate indoor comfort during extreme temperatures; vulnerable population groups such as the elderly or individuals with pre-existing health conditions; and income, which influences coping capacity and recovery potential.

EXPOSURE

Exposure describes the presence, quantity, and spatial distribution of elements that may be affected by climatic or geophysical hazards. It expresses the likelihood that buildings, open spaces, and population are located in areas potentially impacted by extreme events, and thus reflects the extent and characteristics of the elements at risk, whose functionality or integrity could be compromised.

For buildings, exposure is characterized through indicators that describe physical and functional attributes: intended use, building typology, construction age, and conservation status. These parameters allow the identification of building classes that share similar susceptibility to damage and facilitate the spatial mapping of potentially affected structures.

For open spaces, exposure is defined by intended use and typology, capturing the functional role and physical characteristics of urban areas that may influence their response to heat stress or flooding events.

For people, exposure is quantified in terms of population distribution and population density by census unit, representing the number and concentration of individuals potentially exposed to hazardous conditions. These indicators are essential for estimating the scale of human impact under different hazard scenarios.

IMPACT

Impacts refer to the outcomes generated by the combined action of hazard intensity, exposure, and vulnerability, and represent the expected physical, economic, and social losses within the urban system. These are quantified through indicators that link hazard conditions to measurable effects on buildings, population, and infrastructures, ensuring consistency with the multi-risk assessment structure.

For heatwaves, impacts are assessed through the estimated hospitalization costs associated with heat-related illnesses. This indicator provides a comparable measure of societal impact that links climatic stress to public health consequences. For pluvial flooding, impacts are represented through a combination of economic losses related to road cleaning and restoration and damage to buildings and their contents. Together, they capture the immediate economic implications of flooding on the functioning of the urban environment.

For geophysical hazards, impacts are quantified in terms of expected building losses due to seismic events, roof collapses induced by volcanic ash fall, and the resulting number of displaced residents. Seismic impacts reflect the extent of structural damage caused by ground shaking, while ash-fall impacts account for roof failures driven by excessive vertical loading during eruptive events. The number of displaced residents provides a social impact indicator, translating physical damage into consequences for housing availability and population stability.

SYNTHETIC INDEX

To provide a concise overview of multi-risk conditions in the urban system, a Synthetic Index was developed combining ex-ante climate hazard indicators with geophysical impact ones. This index captures both the intensity of climatic hazards and the expected consequences of geophysical events, supporting the identification of areas where urban elements are most susceptible to potential losses under multiple risk scenarios. This hybrid approach – which overlaps information from diverse indicators, namely hazard and impact maps - reflects the different relations that design interventions on building and open spaces have with respect to the H-E-V variables in the case of climatic and geophysical risks: for climatic risks, adaptation measures primarily target hazard intensity by modifying environmental and spatial conditions that amplify heat or flooding, while for geophysical risks, mitigation focuses on reducing exposure and vulnerability through structural reinforcement and functional upgrades to buildings and infrastructure. The index thus serves as a practical tool to guide the prioritization of integrated multi-risk interventions, providing a unified metric to compare the relative importance of different urban areas in terms of overall risk. An equivalent index has been recalculated for the ex-post scenario, enabling assessment of the effectiveness of the implemented measures in reducing combined risk levels.

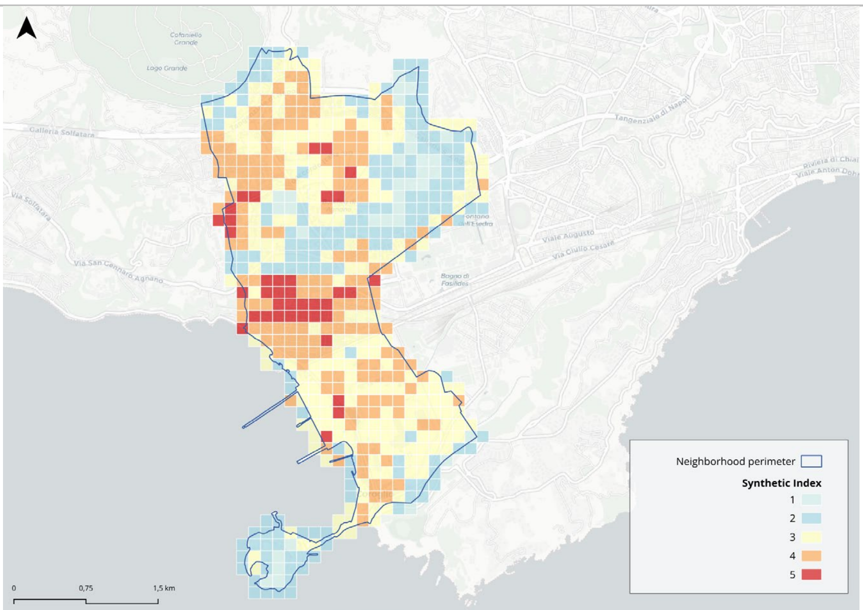

Figure 28. Synthetic Index of ex-ante multi-risk conditions in the Bagnoli district. The index integrates climate hazard indicators with geophysical impact estimates, providing a unified representation of areas where urban elements are most exposed and vulnerable. It reflects the potential intensity of heatwaves and pluvial flooding alongside expected losses from seismic and volcanic events, supporting the identification of priority areas for integrated multi-risk interventions and informing strategies for climate adaptation and disaster risk reduction.

SCENARIO POST

CLIMATIC AND GEOPHYSICAL IMPACTS

The ex-post impact scenario is developed by assuming the implementation of multi-risk design interventions aimed at reducing the impacts of both buildings and open spaces to climatic and geophysical hazards. These measures integrate strategies for climate adaptation and mitigation with interventions for seismic and volcanic risk reduction. While in the ex-ante assessment climatic and geophysical impacts were presented

Separately – reflecting the need to describe the distinct parameters, indicators and modelling frameworks adopted for their analysis – in the ex-post scenario the two dimensions are discussed jointly. This integration reflects the nature of the proposed design solutions, which are conceived as multi-risk strategies capable of simultaneously addressing climate-related stresses and geophysical hazards through a coherent and interconnected set of interventions. For open spaces, the proposed actions are conceived as integrated solutions, each of which simultaneously fulfils a climatic function and a geophysical-emergency function. In this way, they are organized as a single system of multi-risk measures whose everyday operations contribute to climate adaptation and mitigation, while their spatial configuration and performance enable the management of seismic and volcanic crises. Examples include:

- Green Water Squares, wetlands and rain gardens, which mitigate pluvial flooding and reduce surface temperatures, while also functioning as safe, low-exposure gathering points or flexible evacuation nodes during seismic or volcanic emergencies due to their open and unobstructed layout;
- Bioswales, infiltration strips and permeable pavements, which enhance stormwater infiltration and urban cooling, while simultaneously ensuring continuous accessibility and contributing to safer evacuation routes;
- Tree-lined streets, agroforestry systems, biodiversity gardens and renaturalized dune systems, which provide long-term microclimatic regulation, CO_2 absorption and shade, but also act as spatial buffers facilitating crowd movement, visual orientation and local refuge during emergency procedures;
- Modular shaded structures, pergolas and photovoltaic canopies, which deliver thermal comfort and renewable energy in ordinary conditions, and guarantee sheltered, low-risk waiting areas or continuity of critical energy supply during crisis events;

For buildings, the interventions combine energy efficiency measures with structural retrofitting for seismic and volcanic hazards. Energy retrofits were selected to ensure full compatibility with geophysical risk interventions. Photovoltaic panels are installed with an inclination to resist ash deposition, while envelope interventions include ventilated facades or double-skin systems in UHPC, providing high fire resistance (A1) and enhanced out-of-plane performance to withstand pyroclastic flows and support seismic retrofitting by acting as additional structural bracing. For masonry buildings, insulation in rock wool (A1, 1000–1200°C) or hemp fiber (E, 500°C) ensures both thermal efficiency and compatibility with geophysical interventions.

Structural interventions are tailored according to building components:

- Vertical structures: FRCM cladding and confinement, UHPC coatings, and protective barriers;
- Horizontal structures: FRP or FRCM slab reinforcement, steel superstructures for inclined roofs;
- Openings: steel panels, anti-explosion protective films, high-performance shutters and window frames.

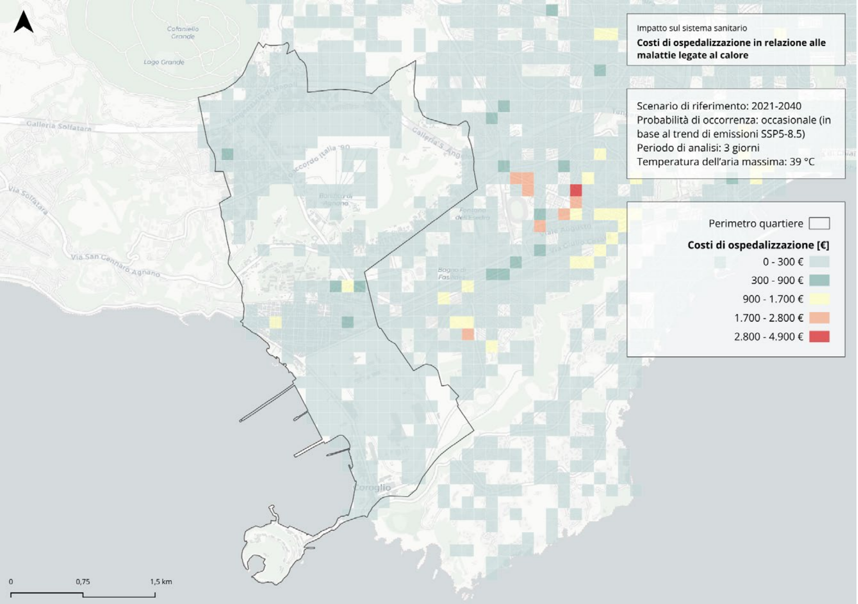

Figure 29. Estimated hospitalization costs associated with heat-stress-related conditions, based on a 3-day heat wave event with a peak air temperature of 39°C, with a probability of occurrence of "occasional" in the period 2021-2040 and "frequent" in the period 2041-2070 based on the SSP5-8.5 emissions trend. The map represents the scenario referring to the implementation of the actions identified by the project.

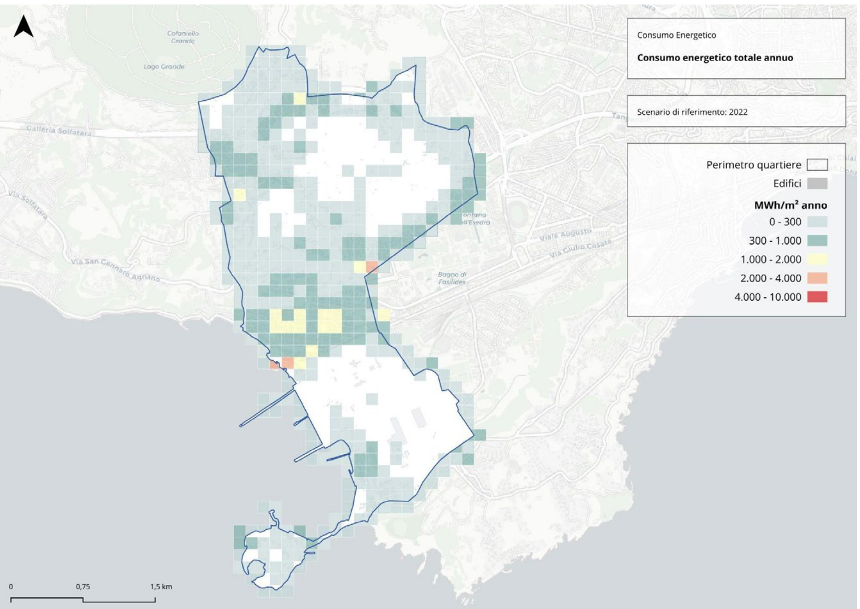

Figure 30. Estimated reduction in energy consumption per m^2 compared to the baseline condition, resulting from the implementation of the project actions. The map represents the ex-post scenario and highlights the spatial distribution of energy demand reductions across the urban area.

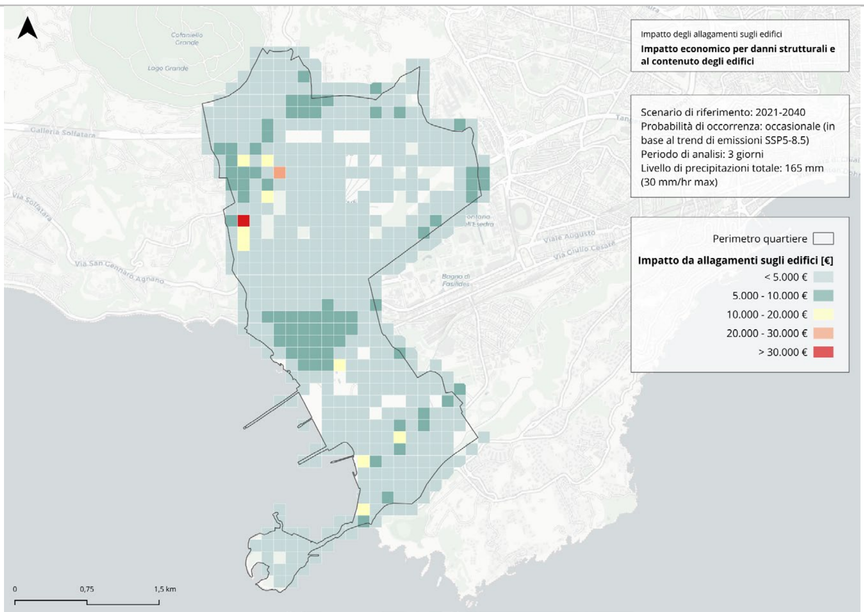

Figure 31. Economic impact due to structural and content damage to buildings resulting from a rainfall event of 165 mm over 3 days, with a peak intensity of 30 mm/hr, corresponding to an “occasional” scenario in the 2021–2040 period and a “frequent” one in the 2041–2070 period, based on the SSP5-8.5 emissions pathway. The map represents the scenario referring to the implementation of the actions identified by the project.

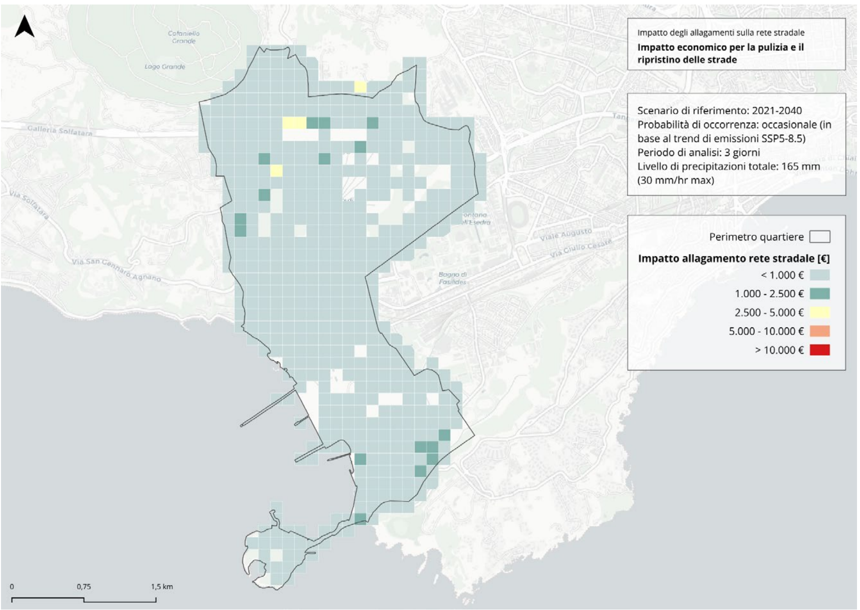

Figure 32. Economic impact of street cleaning and restoration following surface flooding events, associated with a rainfall event of 165 mm over 3 days, with a peak intensity of 30 mm/hr, corresponding to an “occasional” scenario for the period 2021–2040 and a “frequent” scenario for the period 2041–2070, based on the SSP5-8.5 emissions pathway. The map represents the scenario referring to the implementation of the actions identified by the project.

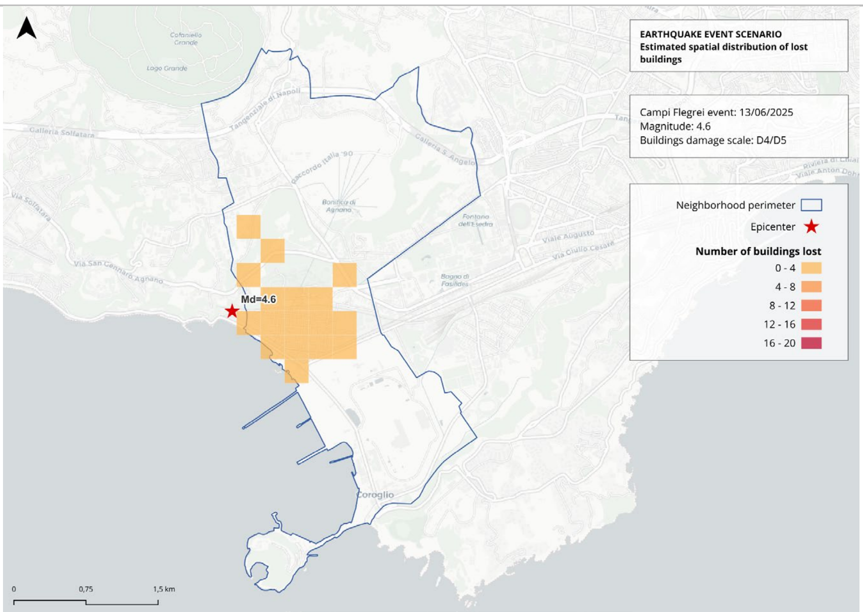

Figure 33. Estimated distribution of collapsed buildings resulting from a magnitude 4.6 earthquake of 13 June 2025 following the implementation of the proposed actions. The map illustrates the expected impacts after project implementation, showing a reduction in the number of collapsed buildings compared to the current conditions, based on the same data and methodology.

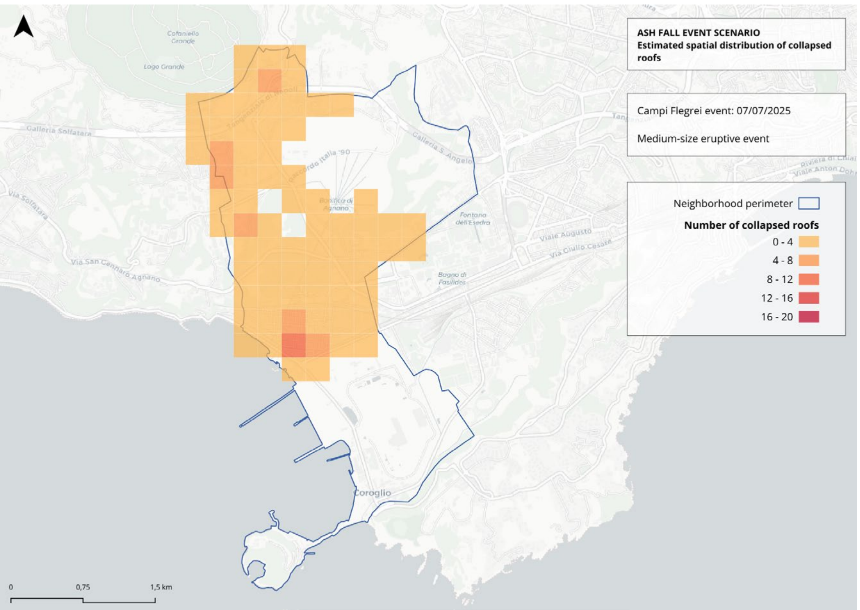

Figure 34. Estimated number of roof collapses caused by ash fallout from a medium-size eruptive event at the Campi Flegrei volcanic area on 07 July 2025 following the implementation of the proposed actions. The map illustrates the expected impacts on building structures after project implementation, showing a reduction in roof collapses compared to current conditions, based on the same data and methodology.

SYNTHETIC IMPACT

This map allows to identify synergies between climate and geophysical adaptation strategies in enhancing the overall resilience of the urban system, reducing expected impacts on both buildings and open spaces under future hazard scenarios. With respect to climate mitigation and CO2 emission reduction, this integrated approach ensures that energy efficiency measures are not only effective in reducing thermal loads and energy consumption but are also compatible with seismic and volcanic safety requirements. The increase of vegetative cover and its potential carbon storage capacity is designed in relation to specific needs of open spaces reorganisation in support of the volcanic emergency management, focusing on planned escape routes and gathering areas.

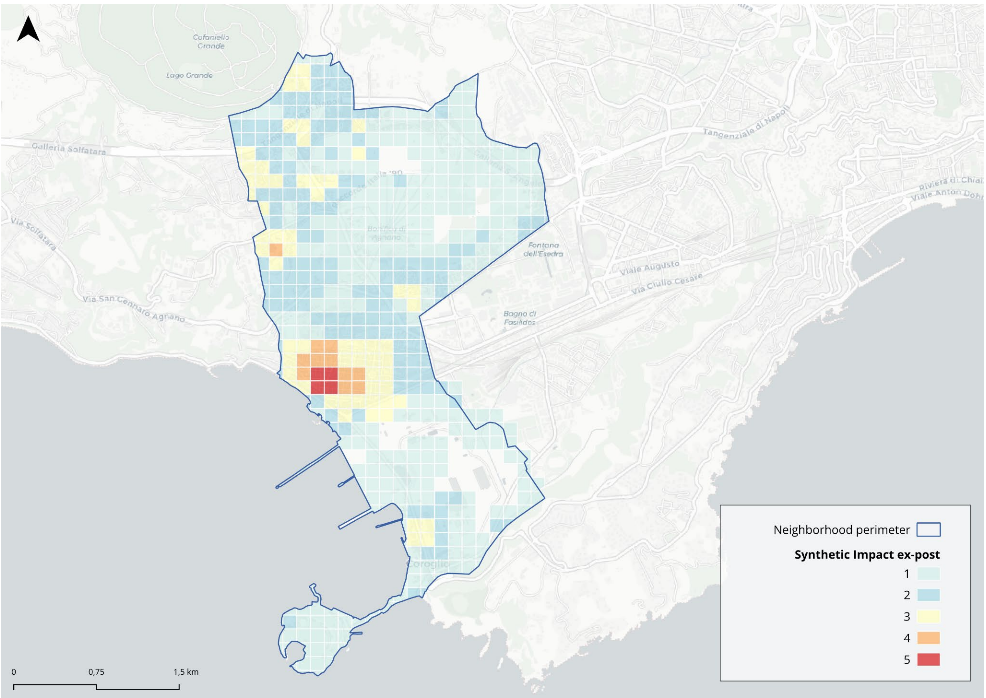

Figure 35. Synthetic impact map of the ex-post scenario for the Bagnoli district. The map provides an integrated assessment of residual multi-risk conditions following the implementation of combined urban interventions. It highlights the reduced expected impacts on buildings, open spaces, and population. It reflects the enhanced resilience achieved through the synergy of energy efficiency, climate adaptation, and structural safety measures. This overview supports the evaluation of intervention effectiveness and the prioritization of further multi-risk strategies.

METRICS POST

CLIMATIC AND GEOPHYSICAL HAZARDS

The indicators used for the assessment of the ex-post scenario remain the same as those adopted in the ex-ante analysis for climatic and geophysical hazards. In the post-intervention condition, however, these indicators are recalculated under the assumption that integrated multi-risk design strategies have been implemented on both buildings and open spaces. Such measures combine climate-oriented adaptation and mitigation actions with structural and spatial interventions aimed at reducing exposure and vulnerability to seismic and volcanic events.

For climatic hazards, both heatwave and flooding indicators are recalculated by accounting for the effects of the implemented passive and active measures.

In the case of heatwaves, the Mean Radiant Temperature (MRT) reflects the improved outdoor thermal environment resulting from increased vegetation cover, shaded areas and high-albedo or permeable surfaces. Indoor conditions are reassessed through the annual energy consumption per unit of floor area, recalculated following building-level energy retrofits such as façade optimization, shading devices and photovoltaic integration. These interventions reduce cooling demand, improve thermal comfort, and contribute to the reduction of associated CO_2 emissions. For rainfall-induced flooding, the probability of inundation is updated by incorporating changes in surface runoff coefficients and soil infiltration capacity resulting from green-blue infrastructure, permeable pavements and nature-based solutions. The modified hydrological behaviour of open spaces affects local drainage conditions, reducing the likelihood and spatial extent of urban flooding.

Geophysical hazard indicators – macroseismic intensities, dynamic pressure of pyroclastic flows and ash-fall load – remain defined by the physical characteristics of the events themselves, but their interaction with the built environment changes in the ex-post condition.

Although the hazard intensity does not vary, its expected effects are recalculated considering the enhanced structural performance of buildings and the reconfiguration of open spaces for emergency management. Structural reinforcement, UHPC/FRCM applications, slab strengthening and protective systems for facades and openings increase the capacity of buildings to withstand shaking, dynamic pressure and ash accumulation. Similarly, redesigned open spaces improve evacuation efficiency and reduce obstruction risks during volcanic fallout, indirectly influencing the way hazard intensity translates into impacts.

VULNERABILITY

Vulnerability indicators for buildings, open spaces and population are recalculated to reflect the reduced susceptibility of these systems following the implementation of integrated interventions.

For buildings, new seismic, pyroclastic-flow and ash-fall vulnerability classes are assigned based on the structural, technological and energy retrofitting actions applied to representative typologies.

For open spaces, NDVI, LST and soil infiltration capacity are updated to account for vegetation increase, permeable surface installation and microclimate-oriented design solutions.

For people, changes in vulnerability indicators – such as UTCI, energy poverty and the exposure of vulnerable groups – capture improvements in outdoor thermal comfort, reductions in indoor overheating, and enhanced accessibility and safety during emergencies.

EXPOSURE

Exposure indicators are updated by integrating the functional and spatial transformations introduced by the multi-risk interventions. For buildings, changes in intended use, typology modifications, improved conservation status or functional upgrades alter the distribution and characteristics of exposed structures.

For open spaces, new configurations determined by nature-based solutions and emergency-oriented layouts redefine their effective exposure to climatic and geophysical hazards.

For population, exposure is recalculated to reflect potential changes in the distribution or density of inhabitants across the study area, particularly in relation to improved accessibility, safety conditions and perceived environmental comfort.

IMPACT

In the ex-post scenario, impacts are updated to reflect the outcomes generated by the interaction between hazard intensity, exposure, and vulnerability after the implementation of the proposed multi-risk design actions.

For heatwaves, they continue to be assessed through the estimated hospitalization costs associated with heat-related illnesses, but these costs are recalculated to account for improved outdoor and indoor thermal conditions. The implementation of vegetation-based solutions, shading systems, high-albedo and permeable surfaces, together with building-level energy retrofitting measures, leads to a reduction in thermal stress and indoor overheating. As a result, the expected health-related impacts and associated healthcare costs are reduced, reflecting an improved capacity of the urban system to cope with extreme heat events.

For pluvial flooding, impacts are recalculated through updated estimates of economic losses related to road cleaning and restoration, as well as damage to buildings and their contents. The introduction of green-blue infrastructure, permeable pavements, bioswales and nature-based drainage systems modifies surface runoff dynamics and enhances infiltration capacity. These interventions reduce the extent and duration of surface water accumulation, leading to lower disruption of mobility networks and a decrease in direct economic losses associated with flooding events.

For geophysical hazards, impacts are re-estimated in terms of expected building losses due to seismic events, roof collapses induced by volcanic ash fall, and the resulting number of displaced residents, accounting for the improved structural performance of the built environment. The application of structural reinforcement techniques, facade and slab strengthening, and roof reconfiguration significantly reduces the likelihood of collapse and severe damage. Consequently, the number of buildings affected and the scale of population displacement are reduced, mitigating both structural and social impacts associated with earthquakes and volcanic activity.

Overall, the ex-post impact assessment highlights how integrated design actions can effectively alter the way hazard conditions translate into losses, reducing expected impacts without modifying hazard intensity itself. This confirms the role of spatial, environmental and structural interventions as key leverage points for multi-risk mitigation and urban resilience.

SYNTHETIC INDEX

The ex-post Synthetic Index integrates updated climate hazard indicators with geophysical impact estimates, reflecting the effects of implemented multi-risk interventions. It provides a unified metric to evaluate how the implemented measures have reduced combined risks, highlight areas where urban systems remain most exposed or vulnerable, and support decision-making for prioritizing ongoing or complementary interventions.

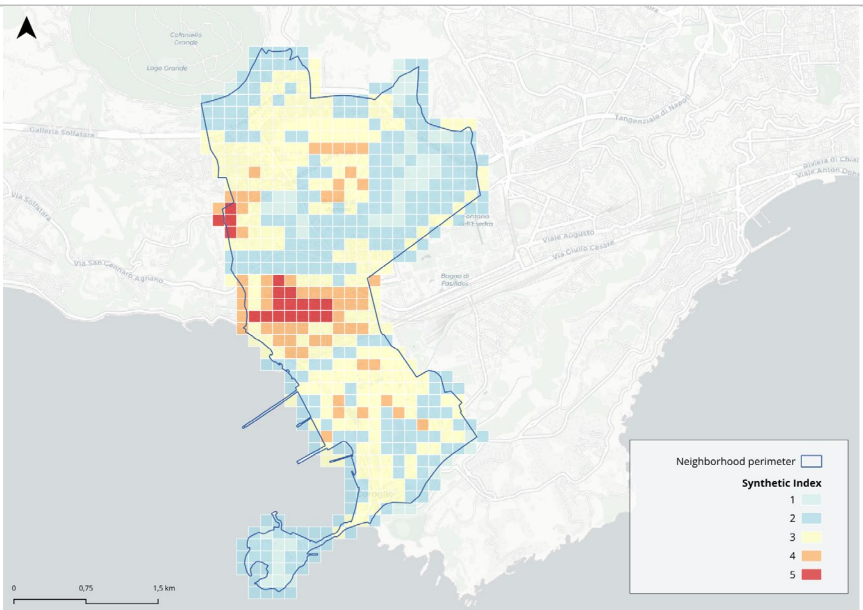

Figure 36. Ex-post Synthetic Index of multi-risk conditions in Bagnoli. The index combines updated climate hazard and geophysical impact indicators, reflecting the effects of implemented interventions on buildings and open spaces.

TOOLS

X Q-GIS	☐ …	☐ …		

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4.5.Impact chain method to evaluate heatwave impacts

WHAT-IF SCENARIOS CASE STUDY COLLECTION
measuring the effect of multi-risk mitigation and adaptation

Impact chain method to evaluate heatwave impacts

M.F. Clemente, S. Puzone, S. Verde, E. Tersigni

RESEARCH UNIT

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TASK RETURN

Task 5.5.3 - The resilient-city simulation test of mitigation and adaptation scenarios

RESEARCH OBJECTIVES

The aim of the research is to define and develop an operational tool useful for systematically representing how one or more hazards interact with vulnerability and exposure factors, resulting in direct and indirect impacts. This multi-risk approach can support both the knowledge phase and the definition of risk adaptation and mitigation strategies, through the integration of different data sources and participatory assessments.

KEYWORDS

Impact chain, Heatwave, multirisk assessment, vulnerability, CO_2 emissions

SCALE

☐ territorial	**X** macro-district	☐ district	☐ census zone		

URBAN CONTEXT

☐ city centre	☐ historic centre	☐ industrial area	☐ periurban area	**X** periphery neighbourhood	

RISK MITIGATED

X heatwave	☐ Pluvial flooding	☐ Seismic	☐ …		

SCENARIO ANTE

In the ANTE scenario, the hazard considered is the heatwave, defined as an extreme event with high intensity and long duration, with direct effects on the overheating of buildings, thermal discomfort, increased energy demand for cooling and high stress on the electricity grid. The residential building stock of Naples is energy-intensive and vulnerable, with limited thermo-physical performance of the envelope and strong exposure of the resident population. The increase in energy demand generates further cascading impacts, including the increase in operational CO_2 emissions and the increase in energy costs for households and administrations, configuring both an economic and environmental risk.

The potential indirect effects related to the vulnerability of the building stock were also considered, such as structural damage, possible injuries or victims and the need for repair or reconstruction interventions, with a consequent increase in embodied energy and carbon.

Based on the impacts identified, the impact chain makes it possible to identify three common macro-categories of risk:

- risks for the health and safety of the population, heatwaves cause negative effects especially for vulnerable populations such as the elderly, children and the chronically ill, also increasing psychosocial risks (such as heat stress for workers in environments with low thermo-hygrometric comfort) (Ministry of Health, 2019);
- financial risks, deriving from the increase in energy costs for cooling and damage to both transport and service supply infrastructures (i.e. energy services);
- environmental risks, with an increase in climate-changing emissions due to greater use of cooling systems but also cascading risks – such as fires and geological instability – due to an alteration of urban biodiversity and water cycles.

The development of impact chains with digital support tools, such as Draw.io software, makes it possible to associate differentiated data and information with the visual representation. A case study is heatwaves, events that will be increasingly intense, frequent and long-lasting in the coming years, requiring the development of decision support tools for risk mitigation.

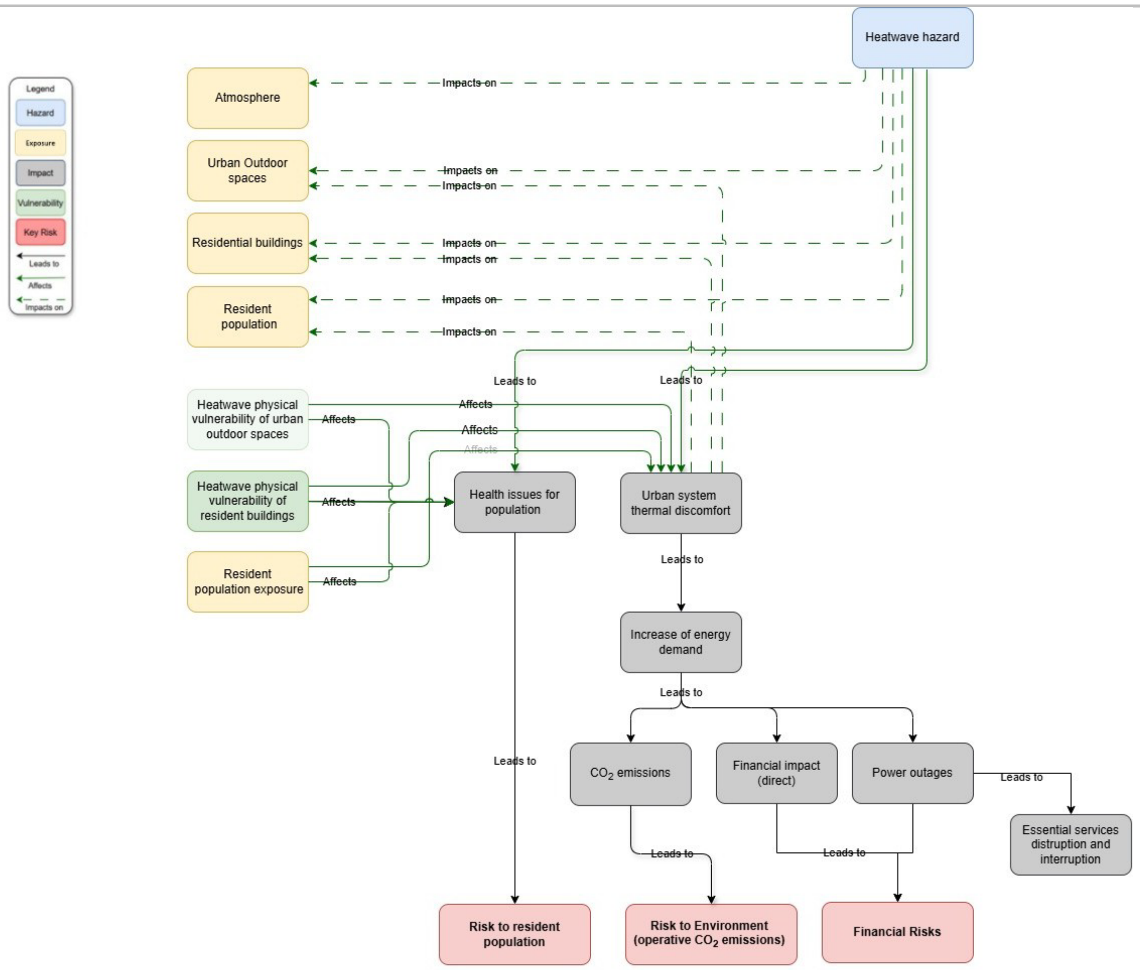

Figure 37. Heatwave impact chain ANTE. Elaborated with software Draw.io

The following factors are identified for the construction of the impact chain: hazard, vulnerability, impacts, exposure and risks. With regard to relationships, four types are identified: leads to (leads to) relationship that identifies direct cause-effect consequences; influence (affect) a relationship that indicates an influence that involves changes but which may not be definitive; impacts on, a relationship that indicates an impact, a tangible and measurable consequence; mitigates (mitigates) report indicating the potential mitigation of impacts resulting from the application of actions for risk reduction (AA.VV., 2025).

METRICS ANTE

Starting from the construction of a multi-hazard knowledge model based on the Geographic Information System (GIS) for heat waves and energy needs and the subject of previous experiments (D'Ambrosio et al., 2023a; 2023b), the impact chain was developed with the information support of the *Draw.io software* for the city of Naples.
The methodological approach integrates three analytical levels:

1. construction of the conceptual risk model, through the identification of hazards, exposed elements, vulnerabilities and impacts;
2. elaboration of causal relationships, through the definition of the "*affects*", "*leads* to" and "*impacts on*" connections between the nodes of the chain;
3. systemic interpretation of impacts, aimed at identifying critical points (*leverage points*) for the definition of adaptation and mitigation strategies and project actions and identification of "*mitigated"* relationships.

The approach was applied to the case study of Naples, a city characterized by a high population density, a heterogeneous building stock in terms of age and construction technique and significant exposure to climatic and natural risks. The implementation of data for the construction of the impact chain was developed starting from elaborations already developed in previous studies considering the heatwave phenomenon as a triggering factor that generates impacts on the different urban subsystems (D'Ambrosio et al., 2023a; 2023b).

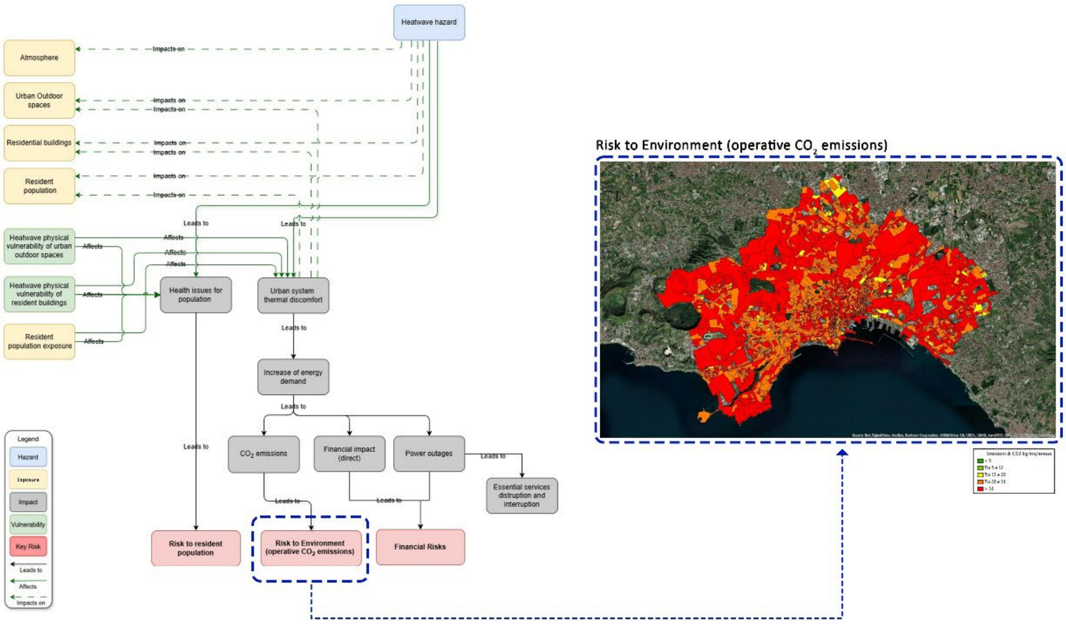

Figure 38. Risk to Environment (operative CO_2 emission) of Heatwave impact chain ANTE. Elaborated with software Draw.io

In particular, the quantitative and qualitative assessment of the impacts of heatwaves on the city of Naples is based on a series of metrics that reflect the intrinsic vulnerability of the building stock and urban infrastructure. CO_2 emissions from residential buildings represent a key indicator: they are recorded at the census section level according to ISTAT 2011 data and organized according to the type of building and the prevailing construction period, revealing an energy-intensive and fragmented heritage in which the oldest buildings have particularly insufficient performance in summer conditions. These emission values are associated with a significant increase in electricity demand linked to the prolonged operation of cooling systems during the heat wave, a phenomenon that accentuates the stress on the electricity grid and can lead to overload phenomena. This generates a condition of infrastructural fragility that increases the risk of blackouts, with widespread consequences both on indoor comfort and on essential services.

SCENARIO POST

In the POST scenario, the factor "Resident building environmental-technological retrofit" is introduced. This factor influences the vulnerability of residential buildings, which in turn causes knock-on impacts on the additional factors involved in the heatwave impact chain.

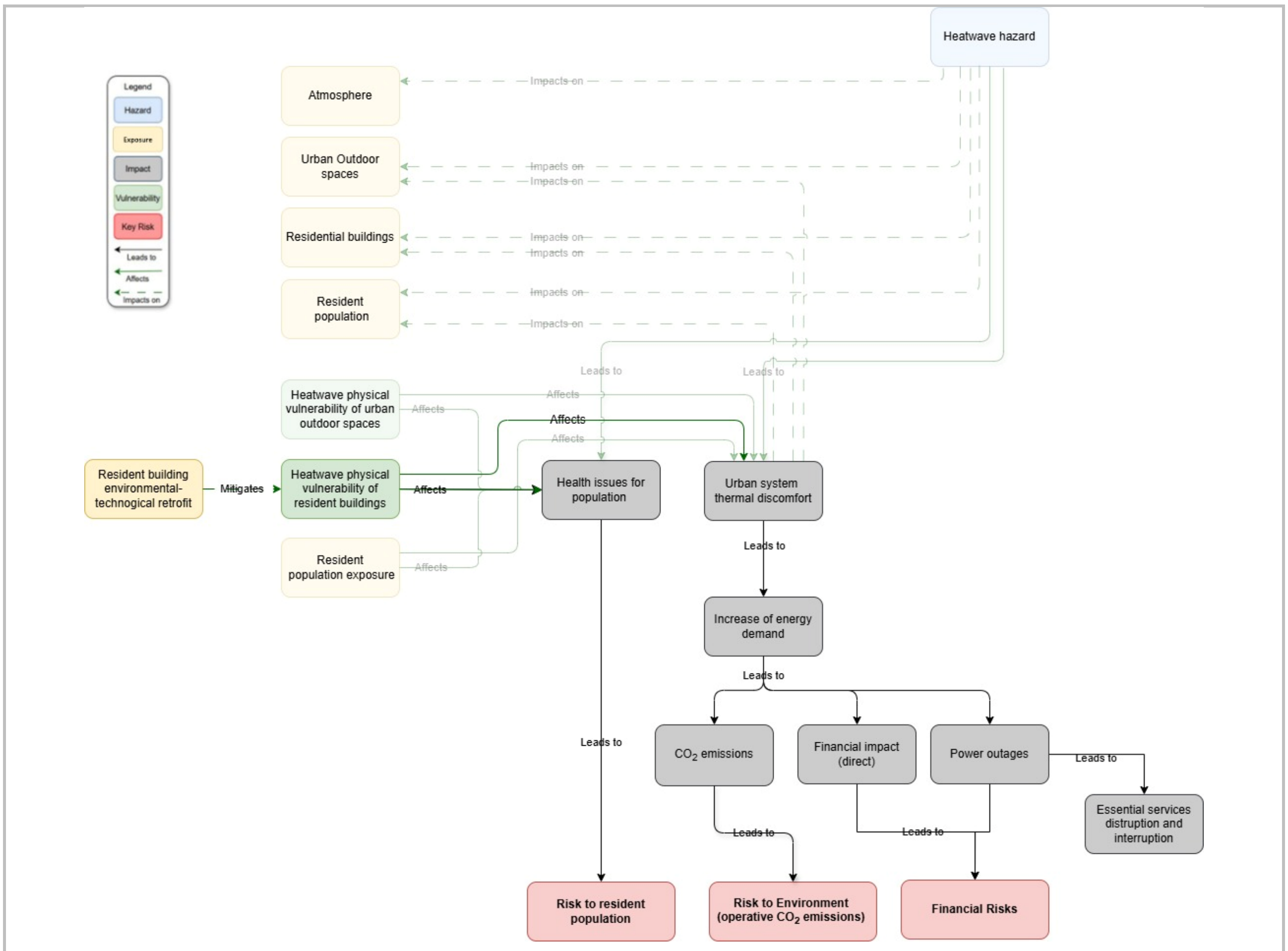

Figure 39. Heatwave impact chain POST. Elaborated with software Draw.io

METRICS POST

The POST scenario uses the same metrics as the ANTE scenario, recalculated under the assumption of implementing active and passive technological retrofit interventions on buildings aimed at mitigating the impacts of heatwaves. Interventions on the building envelope, and subsequently on the building systems, also enable the optimization of energy consumption and contribute to the reduction of CO_2 emissions.

In particular, post-retrofit CO_2 emission values were assigned based on the prevailing building type and the prevailing construction period for each census section (D'Ambrosio et al., 2023a), which highlights how the implementation of retrofit interventions has allowed the significant reduction of CO_2 emissions.

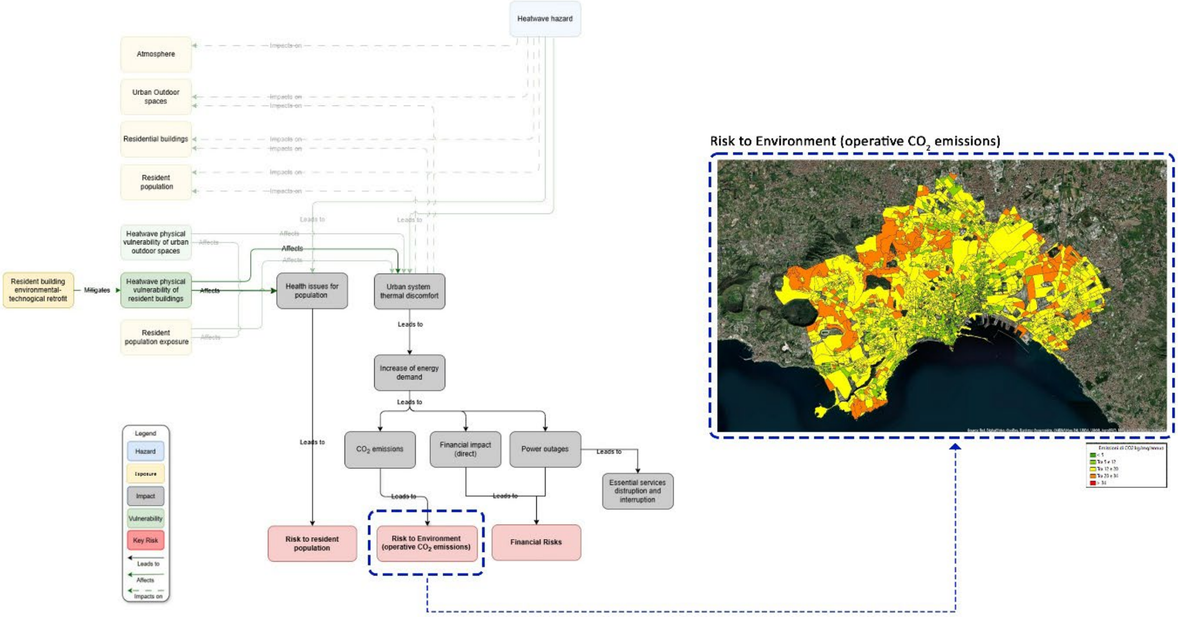

Figure 40. Risk to Environment (operative CO_2 emission) of Heatwave impact chain POST. Elaborated with software Draw.io

TOOLS				
X ESRI ArcGIS Pro 3.5	**X** Draw.io	☐ …		

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5. Future developments: A virtual Test Bed for resilient capacity assessment – Returnville

In the framework of the activities of the Spoke TS1, as an inter-Spoke activity, two virtual cities have been developed: the Coastal Returville (CR) and the Inland Returville (IR) Figure 41. The CR and the IR are two Virtual Testbeds (VTBs) elaborated within the project representing useful instruments for the development, benchmarking, and testing of quantitative community resilience and multi-risk assessment methodologies (Polese et al., 2026). In addition to the construction of the two virtual cities, the research was also focused on the creation of a virtual test bed for the "land" in which the two cities are located: RETURLAND (Liso et al., 2026). The activity, developed within the entire research group of the RETURN project, has seen the involvement of interdisciplinary research groups including engineers, architects and urban planners, sociologists, hydraulic engineers, geologists, etc. The development of the VTBs is conceptualized to be designed as representative of the entire national territory, following the identification of urban archetypes, taxonomies and ontologies, and using real data.

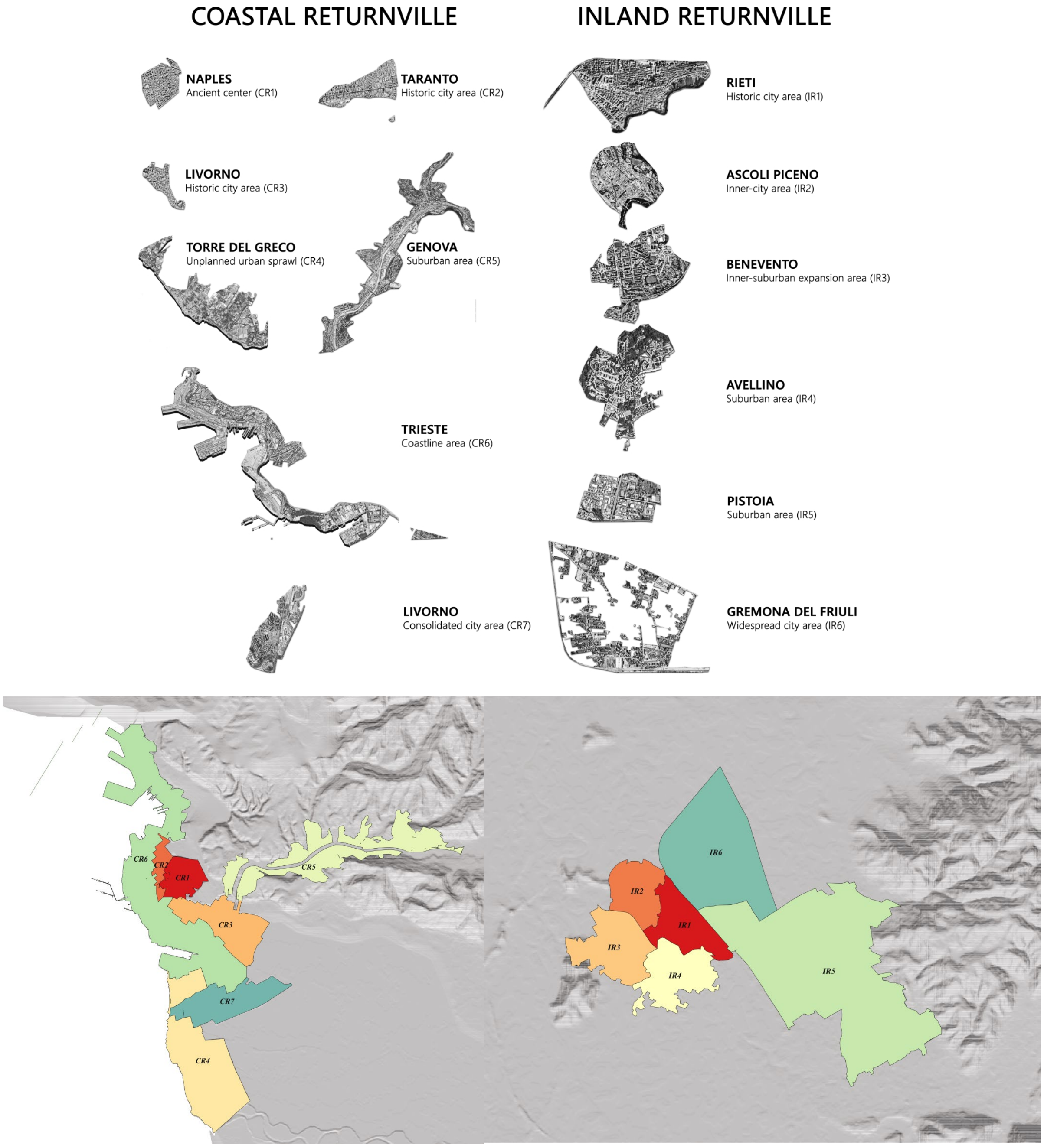

Figure 41. The two virtual cities. Source: Polese et al., 2026.

As the two RETURNVILLE cities and RETURLAND are constructed based on real case studies selected across the national territory and therefore using real and no non-simulated data, the what-if scenarios applied to allow realistic scenarios to be developed. In this context, the development of what-if scenarios in the two virtual cities can highlight certain conditions of hazard, vulnerability and exposure select as representative of specific national context (i.e. the coastal cities and the inland cities) in order to understand the response of the urban system in all its complexity and to test Disaster Risk Management (DRM) and Climate Change Adaptation (CCA) solutions in realistic urban contexts (Polese et al., 2026).

The development of the two virtual cities therefore can support national decision-makers in the implementation of what-if scenarios in order to support them in the transition towards more resilient and livable urban settlements, trough the implementation of environmental, natural, and anthropogenic risk mitigation and adaptation design actions. What-if scenarios, as mentioned in previous paragraph, can be developed starting from the use of specific risk models, risk storylines and impact chains, also taking into account interaction with local stakeholders (Marciano et al., 2024; López-Muñoz et al., 2025; Cocuccioni et al., 2025).

In the two virtual test beds what-if scenarios can be implemented as hypothetical scenarios useful for stakeholder to test and verify the impact of design actions, supporting them through the systemic variation of different variables and parameters (Chen et al., 2024). Hazard and multi-hazard risk assessments methods and models can be simulated with/without risk mitigation and adaptation design interventions and the results in terms of DRM and CCA can be verify by introducing specific indices or indicators, comparing the status of ex-ante and ex-post scenarios (Rome et al., 2016; Nagy & Gutiérrez, 2018; Jayson-Quashigah et al., 2025). Design actions in fact address vulnerability and/or exposure factors consequently mitigating risk impacts. Moreover, multi-hazard risk assessments methods and models developed by researchers can be tested and refined.

6. Conclusions

The research highlights how the concept of the what-if scenario, although widely used in risk planning and assessment processes, is still characterised by significant definitional and methodological heterogeneity. This situation is reflected in the difficulty of developing shared operational approaches, particularly in contemporary urban contexts, where the coexistence and interaction of multiple risks require integrated and comparable analytical tools.

In this context, the research findings suggest interpreting ‘what-if’ scenarios as analytical tools based on the comparison of ex-ante and ex-post configurations, aimed at assessing the impacts of climate adaptation and mitigation strategies. Rather than being predictive tools in a deterministic sense, they take on an exploratory and comparative function, useful for structuring uncertainty and supporting decision-making processes geared towards evaluating alternatives.

The adoption of an indicator-based approach is confirmed as a central component for the operationalisation of such scenarios. Indicators, in fact, make it possible to measure complex dimensions such as vulnerability, exposure and resilience, integrating diverse information and allowing for a multi-scale interpretation of phenomena. The ability to compare different scenarios using coherent sets of indicators is a key element for the transparency and replicability of assessments.

At the same time, there is a need to move beyond single-model approaches by integrating different analytical tools and environments. The multi-platform approach enables models developed for specific purposes to be linked, facilitating the construction of analytical frameworks capable of capturing the interdependencies between climatic, environmental, social and economic components. In this sense, interoperability between platforms and the consistency of indicator systems play a decisive role.

A further key element concerns the systematisation of adaptation and mitigation solutions through structured catalogues. These tools enable project interventions to be organised according to their performance in relation to various risks, whilst highlighting potential co-benefits. This approach helps shift the focus from ad hoc solutions to integrated strategies capable of acting simultaneously across multiple dimensions of urban resilience.

Within this methodological framework, the MUHRA model enables the multi-risk dimension to be explicitly addressed through the aggregation of impacts associated with different hazards and the comparative assessment of scenarios. The ability to include direct and indirect effects, as well as cascading and compound dynamics, is a key aspect for the analysis of complex urban systems.

Applications to case studies demonstrate how the integration of indicators, models and design solutions makes it possible to highlight significant variations in risk levels between ex-ante and ex-post scenarios. At the same time, these applications highlight certain critical issues, including dependence on the availability and quality of data, the difficulty of standardising indicators, and the need to calibrate models to specific contexts.

Looking ahead, the development of advanced simulation environments, such as the Returnville virtual test bed, could help strengthen the operational applicability of the proposed approaches, enabling iterative testing of scenarios and the involvement of various stakeholders in decision-making processes.

Overall, the analysis suggests the need to consolidate integrated, multi-scalar approaches geared towards comparing scenarios, in which 'what-if' scenarios play a central methodological role in supporting the evaluation of strategies and the construction of resilient urban transformation trajectories in the complex context of climate change.

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8. Author's contribution

Even if the Deliverable are unified in their aspects of conception, knowledge framework, methodological approach and experimentation, the contributions have been elaborated as follows:

1. **Introduction** – Valeria D'Ambrosio, Ferdinando Di Martino
2. **Conceptual framework**

- 2.1. Definitions and key concepts
  - 2.1.1. “What if scenario definition. From ex-ante to ex-post scenarios” – UNINA- DiARC, Maria Fabrizia Clemente, Valeria D’Ambrosio, Ferdinando Di Martino.
  - 2.1.2. “What-if scenarios: state of art” – UNINA-DiARC, Ferdinando Di Martino, Angelica Rocco.
  - 2.1.3. “Adaptation, mitigation, resilience capacity” – UNINA-DiARC, Sara Verde.

3. **The proposed methodology**
   - 3.1. “Indicator approach to measure the effects of adaptive and mitigation capacities in single/integrated risk scenarios” – UNINA-DiARC, Sabrina Puzone, Sara Verde.
   - 3.2. “Multi-platform approach to analyze the effect of mitigation and adaptation policies, strategies and actions in case studies” – UNINA-DiARC, Sabrina Puzone, Sara Verde.
   - 3.3. “Adaptation and mitigation solutions catalogues for urban resilience in multi-risk scenarios” – UNINA-DiARC, Bruna Di Palma, Maria Caterina Odelanti, Sabrina Puzone, Enza Tersigni, Sara Verde.
   - 3.4. “Towards the definition of a methodology to characterize what-if scenarios” – UNINA-DiARC, Valeria D’Ambrosio, Ferdinando Di Martino.
4. **Case-study collection of applications of the MUHRA model**
   - 4.1. “Heatwave and pluvial flooding risks in urban areas. A testing in Naples East Area” – UNINA-DiARC, Maria Fabrizia Clemente, Vittorio Miraglia, Sara Verde; PARTHENOPE-DING, Luca Cozzolino, Giada Varra.
   - 4.2. “Heatwave vulnerability assessment. A digital workflow to assess ex ante and ex post scenarios in Soccavo district” – UNINA-DiARC, Giuseppe Mangano, Vittorio Miraglia, Sara Verde.
   - 4.3. “A multifactorial holistic indicator for the monetization of natural capital (VCU) as a multiplier of social added value and relational goods” – UNINA-DiARC, Roberto Cirillo.
   - 4.4. “Climatic and geophysical risks in urban areas. A testing in Bagnoli, Naples” – UNINA-DiARC, PLINIVS-LUPT, UCCRN European Hub, Mattia Federico Leone, Maria Teresa Girardi, Alice Pallotta.
   - 4.5. Impact chain method to evaluate heatwave impacts – UNINA-DiARC, Maria Fabrizia Clemente, Sabrina Puzone, Enza Tersigni, Sara Verde.
5. **Future developments: A virtual Test Bed for resilient capacity assessment – Returnville** - UNINA DiARC, Maria Fabrizia Clemente.
6. **Conclusion** – Valeria D’Ambrosio, Ferdinando Di Martino