

Deliverable D.3.3

Adaptation Options

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Contributors	Karina Izquierdo, Bettina Koelle, Funda Atun, Iuliana Armas, Cosmina Albulescu, Dragos Toma-Danila, Seda Kundak, Betül Ergun Konukçu, Till Wenzel, Hannah Andlinger, Flora Höfler, Philipp Marr, Cees van Westen, Marc van den Homberg
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Abstract
This deliverable describes a selection of three Adaptation/Mitigation options for the four application case study areas of PARATUS: Istanbul, Bucharest, the Brenner Pass (Alps), and the Caribbean. The adaptation options are linked to the impact chains (WP1) and respond to current and future scenarios (WP2). These adaptation options were co-produced with the stakeholders in the region, supported by a series of learning lab processes in each of the four application case study areas. The options are exploring different timeframes, ranging from short-term (1-5 years) to longer-term (up to 30 years). The Adaptation Options also contributed to the development of a serious game, using a range of hazards and adaptation options in an interactive process. This game is inspired by the PARATUS impact chains (WP1) and has been tested in various national and international events (see also the upcoming deliverable, Del 3.4). The Adaptation Options also inspired the development of the Alternative Selection tool, which will be part of the RiskChanges software tool for dynamic multi-hazard risk assessment, which will be presented later in WP4.

Document History

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Disclosure Statement:

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The deliverable D3.3 was submitted to the European Commission on 30 June 2025 and is awaiting approval by the Research Executive Agency. Therefore, this current version may not represent the final version of the deliverable.

About PARATUS:

The PARATUS project aims to enhance the preparedness of first and second responders in the face of multi-hazard events and reduce the risks associated with impacts on various sectors resulting from complex disasters. The outcome is to develop a cloud-based Online Service Platform that offers support in reducing dynamic risk scenarios and systemic vulnerability caused by multi-hazard disasters. To achieve these objectives, the project will perform in-depth assessments of complex interactions between hazards and their resulting impacts in various sectors, analyse the current risk situation and study how alternative future scenarios could change multi-hazard impact chains. Based on this analysis, scenarios of multi-hazard impacts will be co-designed with stakeholders and developed in four case study areas (including the Caribbean, Romania, Istanbul, and Alpine regions).

List of Acronyms

Acronym	Definition
ASFINAG	ASFINAG Alpenstraßen GmbH
CBI	Citizenship By Investment
CDEMA	Caribbean Disaster Emergency Management Agency
D	Deliverable
DRR	Disaster Risk Reduction
DIRA	Dynamic Integrated Risk Assessment
EDF	Economic Diversification Fund
ELER	Earthquake Loss Estimation Routine
EU	European Union
EURAC	EURAC Research
GIS	Geographic Information System
HILP	High Impact Low Probability
IMM	Istanbul Metropolitan Municipality
IPA	Istanbul Planning Agency
ITC	Faculty of Geo-Information Sciences and Earth Observation
ITU	Istanbul Technical University
IMM	Istanbul Metropolitan Municipality
JICA	Japan International Cooperation Agency
KNMI	Royal Netherlands Meteorological Institute
M	Month
LTRG	Long-Term Recovery Group
MHR	Multi-Hazard Risk
NBS	Nature-Based Solutions
NEMO	National Emergency Management Organisation
PARATUS	Increasing Preparedness and Resilience of European Communities by Co-Developing Services Using Dynamic Systemic Risk Assessment
RCCC	Red Cross Red Crescent Climate Centre
RCI	Response Capacity Index
SIDS	Small Island Developing States
SRR	Seismic Risk Reduction
UB	Universitatea din Bucuresti
UNDP	United Nations Development Programme
UNIVIE	Universität Wien
USRI	Urban Seismic Risk Index
UT	University of Twente
WP	Work Package

Executive Summary

D3.3 presents a series of adaptation options for the application case studies of PARATUS. These adaptation options are a result of the iterative Learning Labs and research process in each of the case study areas. Each case study has been analysed under five categories, taking as a reference the European Disaster Resilience Goals¹ to strengthen the disaster prevention, preparedness, and response cycle.

1. **Anticipate** - Improving risk assessment, anticipation and disaster risk management planning;
2. **Prepare** - Increasing risk awareness and preparedness of the population;
3. **Alert** - Enhancing early warning;
4. **Respond** - Enhancing the Union Civil Protection Mechanism response capacity;
5. **Secure** - Ensuring a robust civil protection system.

In this framing, we are considering natural hazards such as earthquakes, hurricanes, extreme precipitation, strong winds, snowstorms and storm surges. Secondary hazards in this context include ecosystem shifts, landslides and avalanches, liquefaction, fires and floods.

The documented adaptation options are prepared to be included in the Online Service Platform of PARATUS. A wide range of adaptation options has been identified across all four application case study areas and are described in this document. Notably, adaptation measures in the context of this deliverable also include mitigation measures to address geological hazards, which are particularly important in the case study areas. The adaptation options discussed here include mitigation measures and explore systemic risk and possible strategies to increase disaster resilience.

The **Bucharest** application Case Study identified three adaptation solutions to a significant earthquake hazard. These were chosen from a range of adaptation options addressing different identified vulnerabilities in the impact chain.

The adaptation options identified were (1) Retrofitting works to strengthen infrastructure elements to enhance resilience; (2) A unified amended law on seismic risk reduction to solve systemic multifaceted risk of earthquakes through a top-down approach; and (3) a decision support system that mitigates key earthquake impacts by using real-time data to optimise emergency responses strategically.

The **Istanbul** application case study identified a potential earthquake exceeding Mw7.0 along the North Anatolian Fault as the primary hazard. Through an intensive stakeholder engagement process, three adaptation options were chosen to address a multi-hazard perspective: (1) dynamic integrated risk assessment to establish an indicator system for planning and implementation; (2) urban regeneration that

¹ https://civil-protection-humanitarian-aid.ec.europa.eu/what/civil-protection/european-disaster-risk-management/european-disaster-resilience-goals_en

could include relocation of residents from high seismic risk areas/buildings to lower risk areas; and (3) Multi-hazard risk assessment to achieve risk-oriented urban planning, including multi-hazard risk.

The application site in the **Alps** faces a range of hazards, including natural events such as landslides, avalanches, rockfalls, and wildfires, as well as anthropogenic threats like transportation accidents, congestion, and overall climate change. The primary hazard identified in this application case study is the occurrence of large landslide events. The identified adaptation options are (1) protection measures to reduce or prevent possible damage with engineering and nature-based approaches; (2) operational adaptations to enhance the response through communication and management practices; and (3) monitoring and early warning to mitigate landslide impact and optimise early warning practices.

The adaptation options proposed for the **Caribbean** Case Study target the impacts and/or vulnerabilities specific to the disaster scenario, focusing on a major hurricane (Category 5) that would hit one or more of the Eastern Caribbean islands—Dominica, Saint Vincent and the Grenadines, and Grenada — in the present or near future. The identified hazard here is a major hurricane, and three adaptation options are presented: (1) constructing Bailey bridges and road asset management systems to ensure flexible and speedy recovery after a major hurricane; (2) shelter planning to select, prepare and plan for sufficient shelters for multi-hazard events for the vulnerable population and (3) citizen investment programmes as a financial mechanism to ensure that the most vulnerable settlements can be relocated.

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1 INTRODUCTION TO WP3 AND D3.3

WP3 is about the existing risk mitigation and adaptation approaches for DRR and Climate Resilience. This includes a compilation of a toolbox and the exploration of adaptation and mitigation options in a co-creation process with a range of stakeholders in the application case study sites.

Deliverable 3.3 focuses on assessing existing and exploring new or amended adaptation options to address specific hazards in the context of compound and cascading risks. In the project process, we collaborated with the stakeholders and academic partners in the case study areas to analyse disaster risk management approaches.

Co-development is the core value of the PARATUS project, and in WP3, we co-develop the adaptation measures together with our partners in the four case study areas. These adaptation options were then examined in a co-production process to assess the robustness for current and future scenarios. In this context, the stress testing guide was developed (Del. 3.2). We used the stress testing methodology in some case study areas to assess the effectiveness of these adaptation options in the case study areas. D3.3 draws input from WP 1 (Task 1.1, Task 1.2) and WP2 (Task 2.1, Task 2.2), and also Task 3.2 in WP3. The results have also been integrated in the development, testing and improvement of serious games, which supported the exploration process and deepened the exploration of adaptation options. The serious games will be documented in the upcoming deliverable D3.4 (M34).

Table 1 Overview of deliverables WP3

#	Name	Due date (month)	Description
D3.1	Virtual compilation of the toolbox	18	Lead Beneficiary: RAN Strategy, case study protocols, including a template for follow-up
D3.2	Guide to stress test future decision making	26	Lead Beneficiary: RCCC A co-produced guide to stress testing decision making.
D3.3	Report of adaptation options	32 (updated to 33)	Lead Beneficiary: RCCC A co-designed guide of adaptation options, resulting from Case Studies.
D3.4	Serious game	34	Lead Beneficiary: CRS One serious game based on immersive user experience has been designed and tested
D3.5	Augmented reality game	44	Lead Beneficiary: CRS One AR game has been designed and tested and is publicly available.

2 BACKGROUND INFORMATION

During the PARATUS project, a series of workshops has been conducted in each application study area, exploring risk through the use of impact chains while learning from the past (WP1). This is followed by the exploration of possible future scenarios (WP2) and the formulation of adaptation options. In these workshops across all application case study areas, the project teams have facilitated an interactive and engaging process, focusing on decisions that mitigate the impact of dynamic multi-hazard scenarios through a participatory co-creation process.

Understanding adaptation solutions requires situating them within the broader landscape of compound and cascading risks. Disasters are rarely singular events; they often involve interconnected threats that unfold in succession or simultaneously, producing amplified impacts across sectors. Historical hazard patterns provide critical insights into how these risks evolve and interact, thereby shaping vulnerabilities over time. Ignoring this complexity can lead to underprepared systems and ineffective responses. The adaptation options presented offer a proactive approach, within a systemic strategy that accounts for the dynamic and layered nature of risk in each of the case study cities.

Impact Chains provide a comprehensive and structured framework for risk analysis. Every case study has developed Impact Chains as a tool to visualise and understand the complexity of multi-hazard risk, including the cascading impacts, and identify vulnerabilities, aiming to identify entry points for risk reduction. The development of these Impact Chains was supported by the forensic analysis of disaster events relevant to the case studies (see Deliverable 1.2).

Following the development of the impact chain, we discussed possible adaptation options under different scenarios in the learning labs for each of the application case study areas, while exploring the robustness of these options. Learning Labs are interactive, multi-stakeholder dialogue processes that allow for the exploration of adaptation options from a systems perspective. During these workshops, we also tested a new complex systems game to explore system dynamics and linking vulnerability to impact and possible adaptation options. This game will be described in more detail in Deliverable 3.4.

This co-production process, involving stakeholders, researchers, and first responders, has explored systems and adaptation options in all application case study areas, resulting in this compilation of adaptation options. The criteria for outlining this summary were jointly developed in an in-person workshop at the University of Twente in March 2025.

In collaboration with the case study leads, a selection of three adaptation options was then described, linked to excerpts of the impact chains to be included in the Disaster Risk Stakeholder platform (<http://drs-hub/eu>). The RiskChanges tool, which is part of the DRS hub, will contain a module where the benefits of various adaptation options can be compared using a Cost-Benefit Analysis, a Cost-Effectiveness Analysis and a Multi-Criteria Evaluation. This will be part of Deliverables D4.4 and D4.5.

3 CASE STUDY ADAPTATION OPTIONS

During the learning lab process in the application case study areas, various adaptation options were explored, considering past, current, and future scenarios. In the context of this work package, we have documented three selected adaptation options for each application case study area. These options cover a range of different approaches and will provide inspiration on how compound and cascading risk can be addressed.

3.1 OVERALL ADAPTATION MEASURES

The adaptation measures presented in this report were co-produced by a diverse group of stakeholders. In documenting these adaptation options, each case study has been analysed under five categories, taking as a reference the European Disaster Resilience Goals (EC, 2023) to strengthen the disaster prevention, preparedness, and response cycle:

1. **Anticipate** - Improving risk assessment, anticipation and disaster risk management planning;
2. **Prepare** - Increasing risk awareness and preparedness of the population;
3. **Alert** - Enhancing early warning;
4. **Respond** - Enhancing the Union Civil Protection Mechanism response capacity;
5. **Secure** - Ensuring a robust civil protection system.

The selected adaptation options are designed to provide a broad range of measures that can be applied in various contexts, serving diverse and often multiple goals across multiple sectors. Some more systemic adaptation options aim to meet multiple disaster resilience goals, thereby impacting planning, awareness raising, and response (e.g., the retrofitting works in Bucharest), while other adaptation options focus on meeting a single goal (e.g., Monitoring and early warning in the Alps).

Each adaptation measure is allocated within the impact chain, aiming to mitigate specific impacts and vulnerabilities identified in the whole system risk mapping.

The suggested adaptation options for each of the case study areas, along with their relationship to the five disaster resilience goals, are documented in Table 2.

All these adaptation options are highly specific to the context in which they have been developed. In a real-life scenario, we would identify a range of adaptation options, address multiple aspects of the impact chain and thus achieve transformative change.

For this deliverable (D3.3), we selected three adaptation options per application case study to demonstrate the range of adaptation options and their potential use, advantages, and limitations.

Table 2 Adaptation options overview and how these relates to the disaster resilience goals.

	Adaptation Option	Goal	Key responses (Anticipate/ Prepare / Alert / Respond / Secure)
Bucharest	Retrofitting works	Strengthening infrastructure elements to enhance resilience	Anticipate: Preservation of key infrastructure Prepare: Awareness raising about secure building codes Respond: More effective response due to less building damage Secure: Providing a robust civil protection service
	A unified amended law on seismic risk reduction	Solving systemic multifaceted risk of earthquakes through a top-down approach	Anticipate: legal framework to reduce seismic risk Secure: Ensure sound and effective response (multifaceted)
	A decision support system	Mitigating key earthquake impacts by using real-time data to strategically optimise emergency responses	Anticipate: Establishing decision support system Respond: Allow for enhanced response capacity Secure: real time data for optimised response
Istanbul	Dynamic integrated risk assessment	Establishing an indicator system for planning and implementation	Anticipate: Indicator system to improve risk assessment Respond: Evaluating institutional and operational capacity to respond to post earthquake emergencies
	Urban regeneration	Relocation of residents from high seismic risk areas / buildings to lower risk areas	Anticipate: Relocation from high-risk areas, managing unplanned developments Prepare: Increased awareness of high-risk area
	Micro zonation	Achieving risk-oriented urban planning, including multi-hazard risk	Anticipate: Strengthens scientific risk assessment and implementation of planning responses
Alps	Protection measures	Reduce or prevent possible damage with engineering and nature-based approaches	Anticipate: Protection measures to anticipate and manage risk
	Operational adaptations	Enhance the operational response through communication and management practices	Anticipate: Scenario based planning Prepare: Communication with road users Alert: Extreme weather event forecasts and road closures Respond: Improved management of disruptive events
	Monitoring and early warning	Mitigating landslide impact and optimising early warning practices	Alert: Early warning for extreme events
Caribbean	Constructing Bailey bridges and road asset management systems	Ensuring a flexible and speedy recovery after a major hurricane	Respond: Bailey bridges allow the response of emergency services and light traffic post-hurricane events
	Shelter planning	Select, prepare and plan for sufficient shelters for multi-hazard events for the vulnerable population	Anticipate: Improved shelter provision and access Prepare: Improved communication on shelter use and deployment of social protection systems (such as emergency cash transfers and food distribution).
	Citizen investment	Finance mechanism to ensure most vulnerable settlements can be relocated	Anticipate: Generate finance for building resilient societies and systems

3.2 BUCHAREST CASE STUDY OVERVIEW

The adaptation options proposed for the Bucharest Case Study target the impacts and/or vulnerabilities specific to the disaster scenario, focusing on a major earthquake (magnitude 7 or greater) that would hit Bucharest in the present or near future. These mitigation measures do not address the seismic hazard, as earthquakes cannot be altered by human intervention; however, their impacts and the conditions arising from various processes and factors (i.e., vulnerability) can be mitigated.

The major Vrancea earthquakes on November 10, 1940 (Mw 7.7, 150 km depth) and March 4, 1977 (Mw 7.4, 94 km depth) have been the most damaging in Romania's and the city's history. These two events shared similarities in their manifestations, with the most recent event, however, continuing the damage initiated by the first. Before 1900, information and the complexity level of society were more limited; some aspects, such as the importance of fire as an additional hazard or the problems of water wells and chimney collapse, began to become less relevant after 1900. On the other hand, the 20th century came with a different challenge: the problem of vulnerable high-rise reinforced concrete buildings. The present and expected future can also be treated distinctively, as traffic became a significant hazard, but also the building and socio-economic vulnerability.

In total, we found 33 adaptation measures. The result draws on the insights of a wide range of stakeholders, including first responders, military personnel, policy and decision-makers, critical infrastructure operators, legal experts, and representatives of insurance companies. These stakeholders engaged in one-on-one interviews designed to leverage their knowledge and expertise. All the options are listed in detail in Annex 1. Herewith, in this section, we discuss in detail three options:

- Retrofitting works
- Amended legal framework to regulate seismic risk reduction
- Decision support system

Data collected through these qualitative methods was meticulously analysed and structured into primary and secondary hazards, impacts, exposed elements, vulnerabilities, susceptibilities, or adaptation options. This was complemented by expert knowledge. In the case of vulnerabilities (which convey already existing conditions), adaptation options (which can also be implemented to mitigate the existing vulnerabilities, prior to the manifestation of the seismic event), and certain impacts that involve simulations (e.g., on road disruption and restricted access to intervention areas, human loss, building damage) scientific literature and official reports were also consulted.

3.2.1 RETROFITTING WORKS

Retrofitting is a technical solution that technical evaluators can recommend upon assessing the state of a building or infrastructure element with notable physical vulnerability to earthquakes (Figure 1). It aims to improve the response of the building/infrastructure element to seismic movements and to ensure the safety of its occupants. The process can refer to the reinforcing of structural elements (such as beams and columns) to enhance earthquake resistance or adding new supporting elements (which might also include seismic

isolation systems), adding fire safety measures, replacing outdated electrical or plumbing systems, or improving insulation and windows for better energy efficiency.

By addressing the high physical vulnerability, this adaptation option ultimately reduces building damage, the number of injured people or deaths, as well as economic loss in the event of a major earthquake. According to the interviewed representative of the Municipal Administration for the retrofitting of buildings with seismic risk in Bucharest, 147 buildings are currently being managed for seismic risk reduction, with various stages of the process underway (including retrofitting). In 2024, 20 to 30 buildings in Bucharest were planned for retrofitting (Figure 2).

Limitations and challenges

Retrofitting works require substantial funding and extend over long periods of time. During such interventions, residents must be relocated for safety reasons and to facilitate effective implementation. Additionally, due to interventions such as jacketing the walls or introducing new structural elements, their apartments often lose their size or configuration. Therefore, this adaptation option is unpopular among the general population. Without public consent for relocation, the retrofitting process cannot proceed. Additionally, the state's capacity to accommodate the relocated population is limited, further impeding the progress of these works.

Additionally, historical buildings (which are often significantly vulnerable to earthquakes and haven't been seismically designed) pose even greater challenges, as retrofitting must not alter the value of these monuments.

Retrofitting works are mandated following a technical evaluation of buildings that were assigned the first (Rs I) risk class. Mayors of municipalities located in areas with peak ground acceleration of 0.15 g or higher (based on the seismic zonation map in Romania currently published in P100-1 from 2013, with a mean return period of 225 years) are required to identify the multi-storey buildings constructed prior to the enforcement of modern seismic design standards (i.e. before 1978), and the ones that were previously assigned risk classes. They must publish the resulting list of buildings and formally notify the owners (natural and legal persons) and the owners' association, and the legal persons who manage residential buildings with Rs I, regarding their obligations to initiate technical expertise. In practice, the visual inspections for the identification of the stated buildings were not performed on time due to delays in the issuance of Methodological norms. These delays have postponed visual inspections, technical assessments, and consequently, the initiation of retrofitting measures.

Another challenge refers to the cumbersome and frequently amended legal framework regulating seismic risk reduction in Romania. This framework has been modified more than 20 times since the country transitioned to democracy. Legal experts interviewed to explore the legislative roots of seismic risk reduction in urban areas highlighted several legislative vulnerabilities that hinder the progression of retrofitting works in Bucharest and across Romania (see the [Impact Chain on the possible effects of a major earthquake that would hit Bucharest](#) in the present or near future). These include inconsistent financial support mechanisms

and onerous bureaucratic procedures required to access funding, both of which hinder retrofitting and contribute to the continued deterioration of structurally vulnerable buildings.

It is only recently that an improved National Programme to consolidate the buildings with high seismic risk was established by Law no. 212/2022, offering a more optimistic outlook for the future of retrofitting initiatives. Moreover, Law no. 243/2023 stipulates that owners or homeowner associations of buildings classified under Risk Class I or II may apply for state-guaranteed loans to finance necessary interventions. Under this law, the state acts as a co-signer and assumes responsibility for repaying the debt.

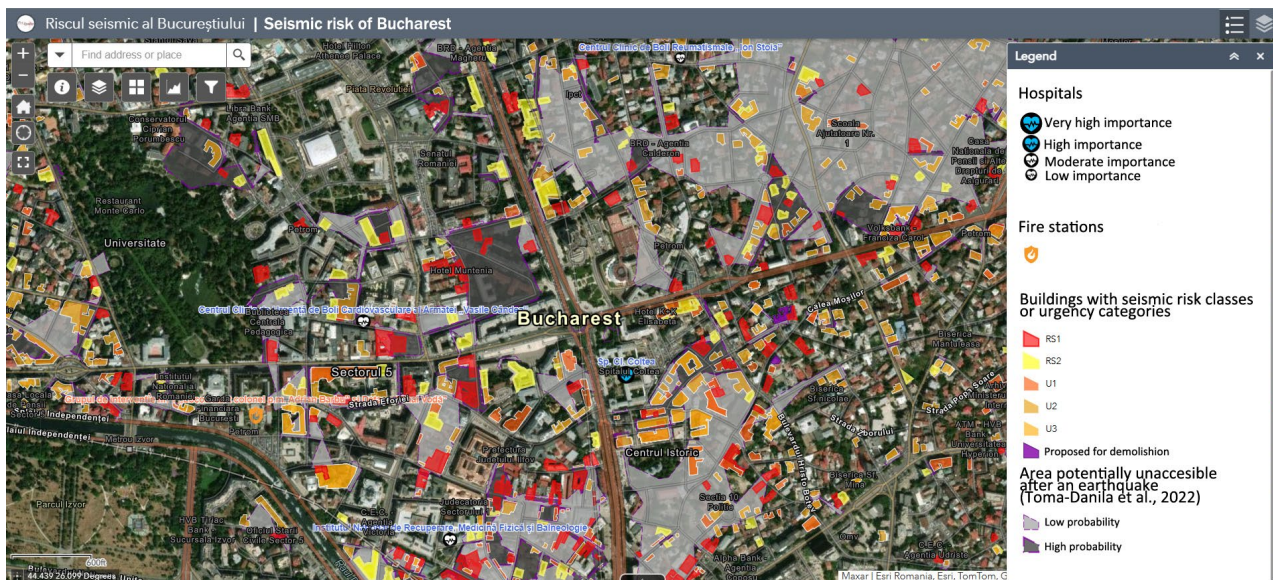


Figure 1 Extract of the interactive map showing the Seismic risk of Bucharest developed by Toma-Dănilă (2022)



Figure 2 Selection of buildings planned for retrofitting in Bucharest

Impact Chain, before and after the implementation

When the focus of the Impact Chain is extended to the indirect mitigation (i.e., targeting second-order elements), the number of connected elements (i.e., vulnerabilities, impacts, and related adaptation options) rises to 67, showing the far-reaching influence of this adaptation option in the Impact Chain.

Figure 3 illustrates the 7 elements connected to retrofitting works. This includes 5 impacts directly mitigated by the proposed measure (damage to water infrastructure, buildings, critical facilities, transportation infrastructure and emergency management buildings) and one physical vulnerability (degradation of structures due to age, damage from previous earthquakes, illegal modifications, and improper repair). The success of retrofitting works is also closely linked (“relates to”) to another adaptation option, namely the increased funding support for retrofitting from the state or from other sources.

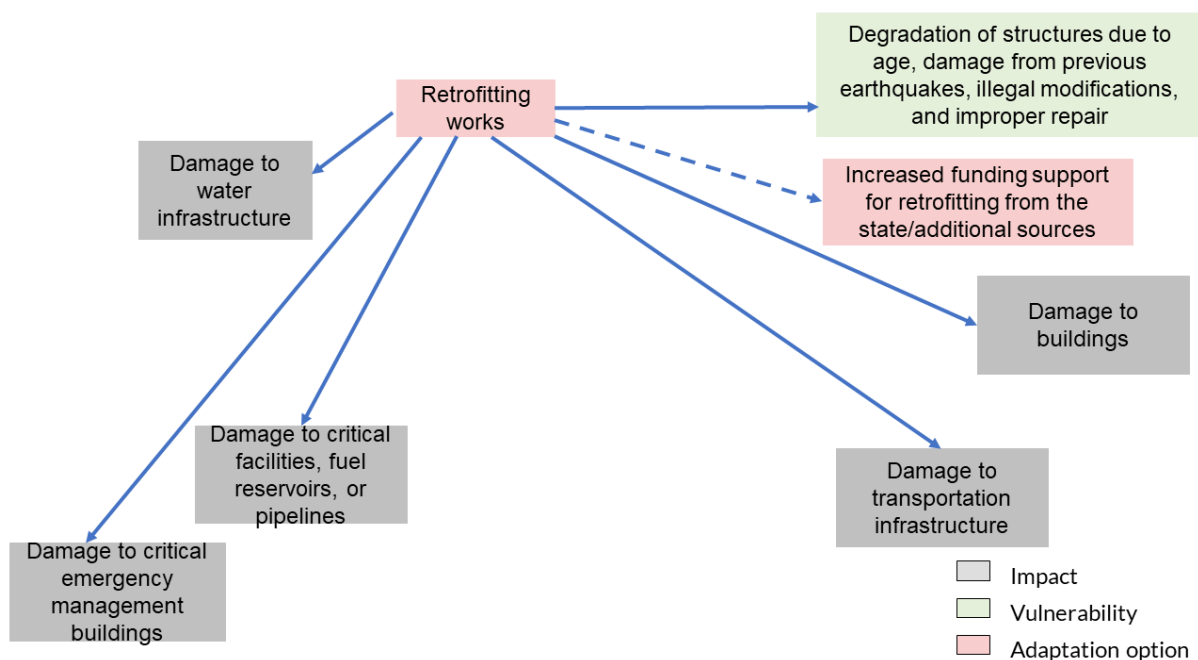


Figure 3: Snapshot of the Impact Chain on the effects of a major earthquake that would hit Bucharest during present times or in the near future, focused on the adaptation option “Retrofitting works”. The blue lines indicate a reduction in impact or vulnerability.

How does the adaptation solution modify risk reduction?

The adaptation option of retrofitting addresses mainly earthquake impacts on infrastructure (Figure 3): damage to buildings (including critical emergency management buildings, such as hospitals or fire stations), transportation and water infrastructure, critical facilities, fuel reservoirs, or pipelines. Strengthening infrastructure elements enhances their resilience against collapse or severe damage during a major earthquake, thereby indirectly saving the lives of occupants and reducing potential economic losses.

Another important physical vulnerability addressed by retrofitting works is the degradation of structures caused by ageing, damage from previous earthquakes, illegal modifications, and improper repair. Retrofitting interventions involve a comprehensive review of both structural and non-structural components of buildings or infrastructure, identifying modifications that compromise their integrity, followed by corrective measures to restore and enhance their resistance.

Can they be represented by maps?

Retrofitted buildings can be mapped, facilitating the monitoring of seismic risk reduction progress. There are no official maps of retrofitted buildings, but those that have undergone technical assessment were mapped by Toma-Dănilă (2022), as illustrated in Figure 1.

3.2.2 ELABORATION OF A UNIFIED, AMENDED LEGAL FRAMEWORK REGULATING SEISMIC RISK REDUCTION

One of the most far-reaching adaptation options that should be implemented in the Bucharest Case Study is the elaboration of a unified, updated legal framework that regulates seismic risk reduction. This measure has been highlighted across all the interviews with legal experts who reviewed the normative acts in question, as well as by the decision-makers from the Department for Seismic Risk Reduction of the Bucharest City Hall.

The legal framework that regulates seismic risk reduction in Romania has been modified more than 22 times and published 4 times (Figure 4) since the fall of the communist regime (1989). These changes have led to a cumbersome legal framework whose ineffectiveness stems from difficulties in its understanding and application, with implications for the insubstantial progress made towards reducing the vulnerability of the building stock in urban areas.

Consolidating all the modifications of the core normative act (Government Ordinance no. 20/1994) in a cohesive legal framework would address the current ambiguity in planning, coordinating, and implementing seismic risk reduction measures. This should be accompanied by updated Methodological Norms and should serve as the foundation of the National Strategy for Seismic Risk Reduction. The forensic analysis has already categorised the vulnerabilities in 5 dimensions. This framework should also include provisions that eliminate other legislative vulnerabilities included in the Impact Chain: the ambiguity in setting the responsibilities of public authorities; the high-level bureaucracy to access retrofitting funding; the lack of a protocol for collecting data on buildings; and deficient urban planning. It should also include legal provisions (e.g., warning liberties for the applicants of the law) that mitigate the weak enforcement of the seismic risk reduction legal framework. Legal experts advise against changing the new legal framework for at least five years in order for it to produce the desired effects.

Limitations and challenges

The primary challenge in implementing this adaptation measure stems from the limited awareness among policymakers and decision-makers regarding its critical importance. The adaptation option was proposed by all interviewed legal experts, who detailed its urgent need and key role in addressing not only legislative vulnerabilities but also physical and socio-economic vulnerabilities that stand behind key impacts of a potential major earthquake. While consolidating all amendments to the core legislative framework for seismic risk reduction (Government Ordinance no. 20/1994) would demand significant effort and time, the long-term benefits of this adaptation option far outweigh these challenges.

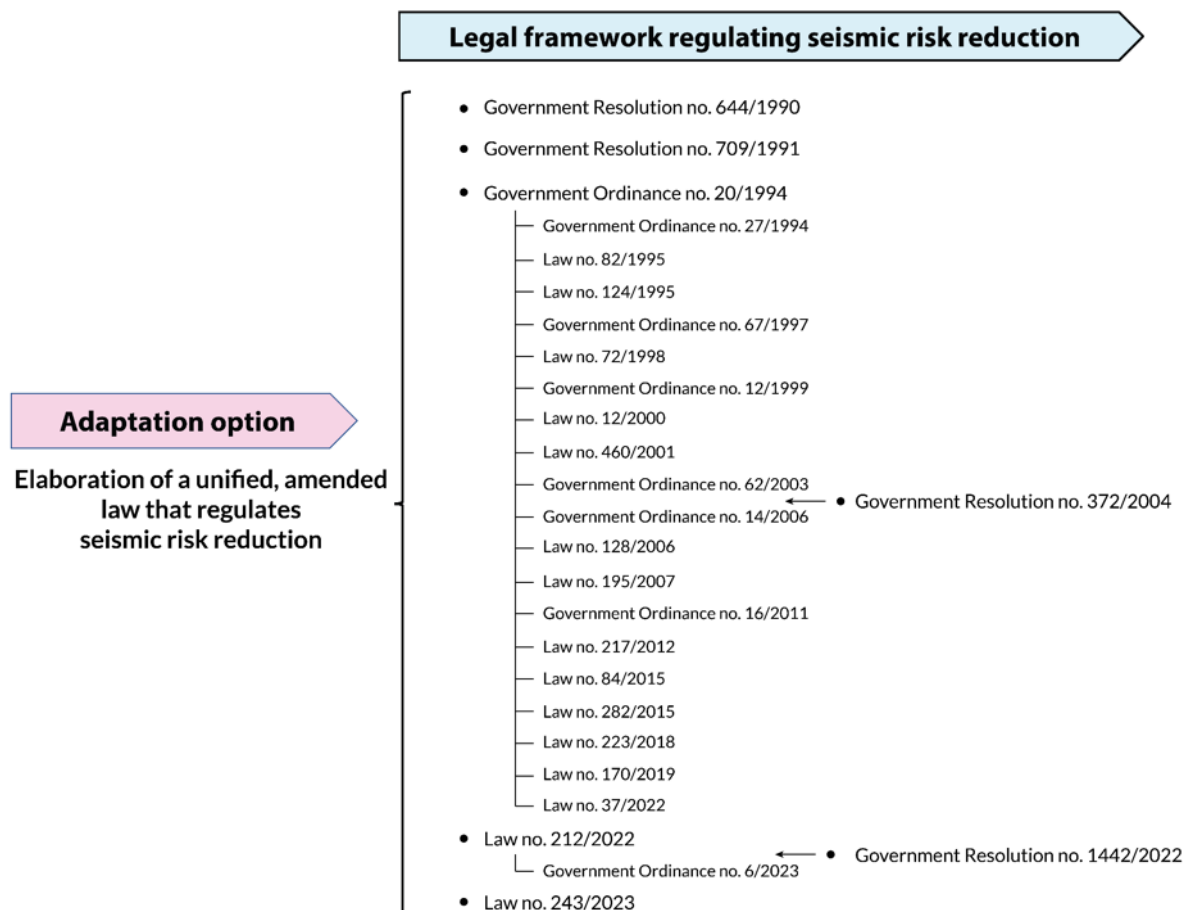


Figure 4 List of the normative acts included in the legal framework that regulates seismic risk reduction in Romania (1989-2023)

Impact Chain, before and after the implementation

The elements connected to the adaptation option of interest (elaboration of a unified, amended law that regulates seismic risk reduction) are illustrated in Figure 5. This includes 6 vulnerabilities directly mitigated by the proposed measure: a cumbersome and ineffective seismic risk reduction legal framework; high-level bureaucracy to access retrofitting funding; little progress in seismic risk reduction; deficient urban development; absence of legal provisions on building data collection; and weak law enforcement (and confusion). When the focus of the Impact Chain is extended to the indirect mitigation (i.e., targeting second-order elements), the number of connected elements (i.e., vulnerabilities, impacts, and related adaptation options) rises to 30.

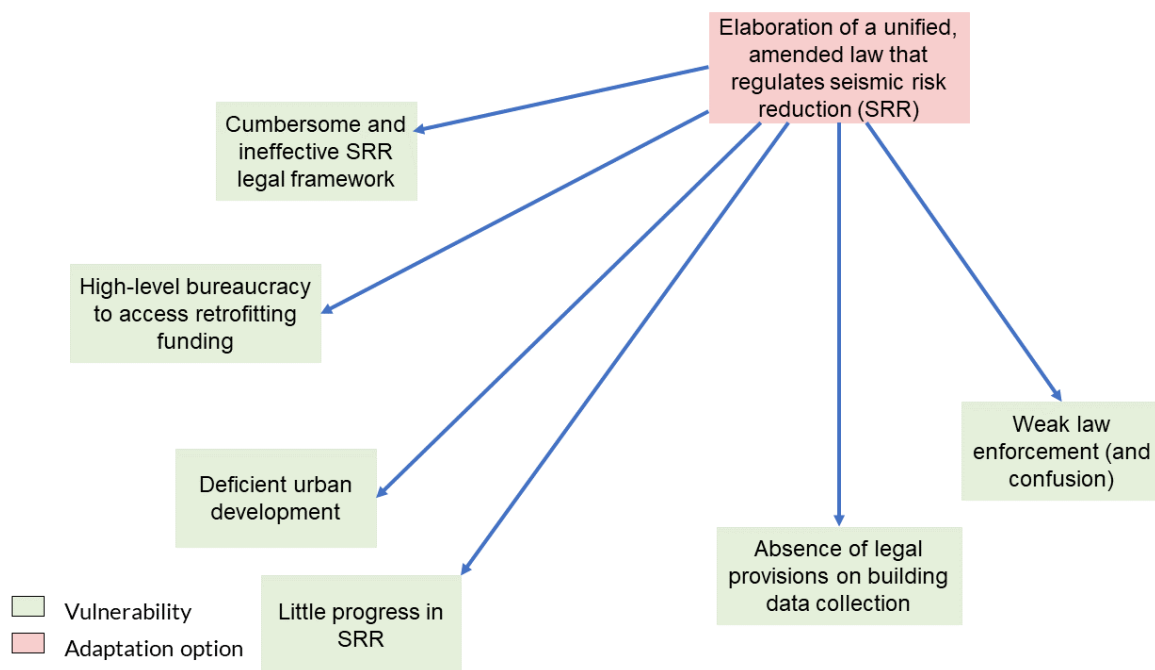


Figure 5 Snapshot of the Impact Chain on the effects of a major earthquake that would hit Bucharest during present times or in the near future, focused on the adaptation option “Elaboration of a unified, amended law that regulates seismic risk reduction”

How does the adaptation solution modify risk reduction?

This adaptation option mitigates numerous legislative vulnerabilities that stand behind key physical (e.g., uncertainty on the number and location of vulnerable buildings; degradation of structures due to age, damage from previous earthquakes, illegal modifications, and improper repair; limited or no seismic design; illegal construction of buildings; absence of a retrofitting plan at the municipal level, etc.) or socio-economic (e.g., corruption, businesses at the ground floor of buildings with high seismic risk - Rs I) and impacts (e.g., damage to buildings, homelessness, etc.).

This means that seismic risk reduction has to be thoroughly planned at the legislative level (through the proposed adaptation option) before real, positive change can be observed at the physical or social levels. Therefore, this initiative underscores the primary role of top-down approaches in solving multifaceted and deeply rooted vulnerabilities to earthquakes.

Can they be represented by maps?

The direct effects of the adaptation options cannot be mapped, as the adaptation option operates at the level of legislative measures. However, its indirect consequences (i.e., progress in seismic risk reduction) can be observed, quantified, and mapped through the number of buildings that will be technically assessed, retrofitted, or demolished.

3.2.3 DECISION-SUPPORT SYSTEMS

Decision-support systems are a cornerstone of Bucharest's earthquake adaptation strategy, designed to target a wide range of seismic impacts and institutional vulnerabilities.

Decision-support systems can significantly improve the limited first response to a powerful earthquake in Bucharest. These systems integrate data from Earthquake Early Warning Systems, ShakeMaps seismic loss estimates, and results of seismic vulnerability analyses (Armaş, 2012; Armaş and Gavriş, 2013; Armaş et al., 2016; 2017), enabling data-driven emergency response coordination and tailored, real-time disaster preparedness communication (Figure 6). By transforming fragmented data into coordinated action, decision-support systems streamline decision-making for emergency management services but also aid in the development of Disaster Risk Management strategies tailored for specific disaster scenarios in Bucharest.

The PARATUS Project aims to provide the Department for Emergency Situations with a system that can prevent the unfolding of important impacts (e.g., human casualties, restricted access to intervention sites, limited treatment capacity and distribution) and alleviate prominent vulnerabilities (e.g., a lack of information support in prioritising interventions and decision-making support systems, the absence of evacuation and accommodation strategies).

Currently, the Network-Risk tool developed by Toma-Danila et al. (2020, 2022) provides limited support in decision-making, requiring GIS knowledge and skills. This tool can be integrated into the PARATUS Platform to enhance its capabilities.

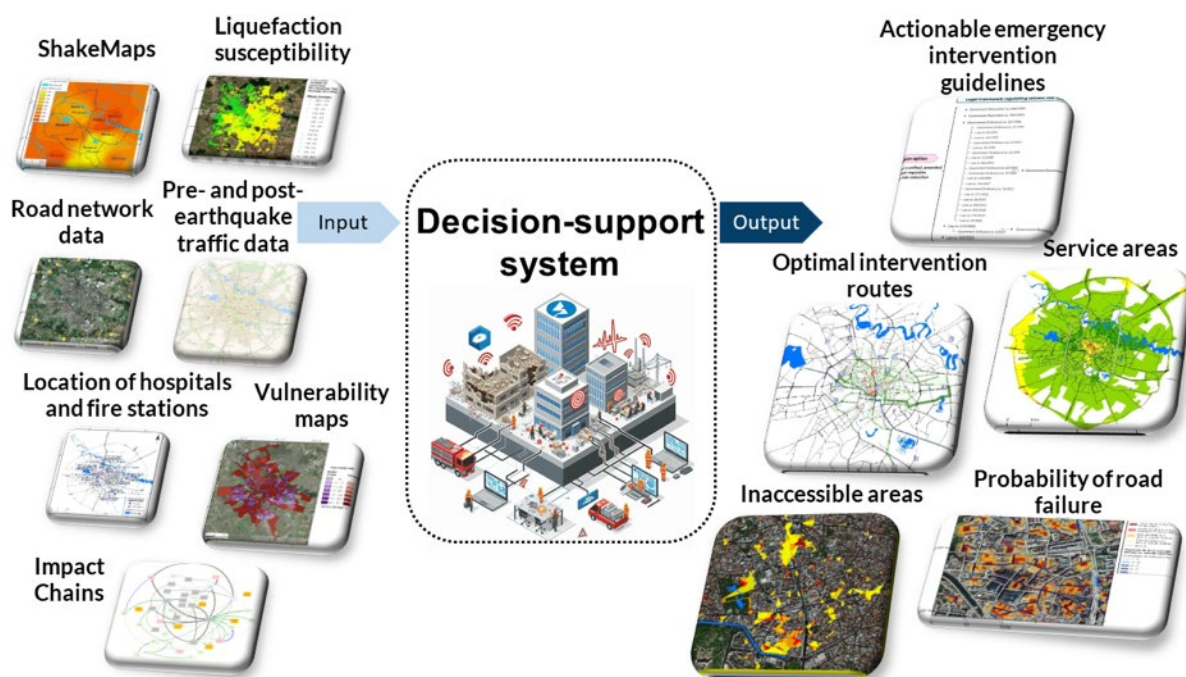


Figure 6 Inputs and outputs of decision-support systems tailored for the earthquake disaster scenario in Bucharest

Limitations and challenges

Decision-support systems rely on up-to-date datasets of hazard, exposure, vulnerability, and risk data, as well as real-time visualisation of intervention areas, to generate actionable recommendations for emergency interventions in the event of a seismic disaster. Acquiring such data, especially in the case of vulnerability

and risk, can be challenging due to inconsistent data collection methodologies, lack of standardisation, restricted access to sensitive information, and insufficient institutional capacity or coordination among emergency management services. Additionally, monitoring infrastructure (including seismic monitoring systems) is essential to provide real-time data and visual representations for Bucharest. In the absence of these data inputs, the outputs of decision-support systems are constrained and may fall short of effectively supporting emergency decision-making. Of course, one limitation is that modelling and data include some levels of uncertainty. Another limitation is that practitioners must be trained in the use of the decision support systems – requiring capacity development and integration of the tool in decision making processes.

Another challenge related to decision-support systems concerns the integration of existing institutional frameworks and these digital tools able to streamline emergency interventions during and after a powerful earthquake. The adoption of such systems can bring to light issues related to outdated or fragmented protocols that limit first response and further postpone the realisation of the benefits that decision-support systems offer for Disaster Risk Management.

Impact Chain, before and after the implementation

Figure 7 illustrates the 8 elements mitigated or related to the selected adaptation option. These include impacts (i.e., limited first response; restricted access to intervention site; human casualties), vulnerabilities (e.g., limited treatment capacity and distribution; lack of evacuation and accommodation strategies; lack of information support in prioritising interventions and decision-making support systems; insufficient first responders), and the adaptation option regarding elaboration of efficient evacuation procedures. When the scope of the Impact Chain is broadened to include indirect effects (i.e., second-order elements), the number of interconnected elements increases to 61.

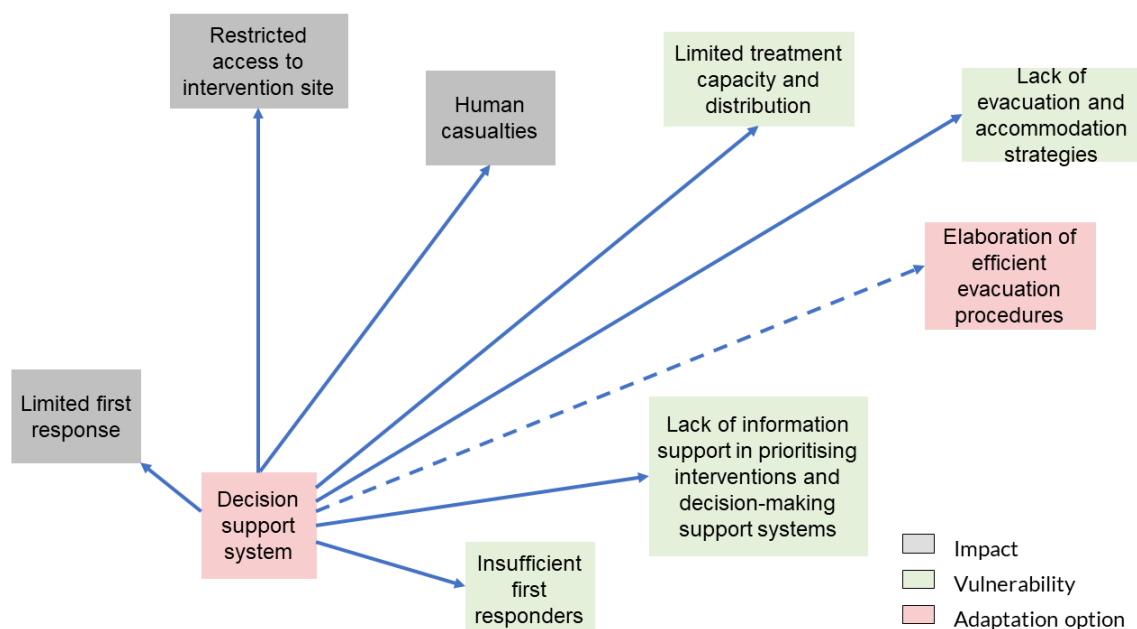


Figure 7 Snapshot of the Impact Chain on the effects of a major earthquake that would hit Bucharest during present times or in the near future, focused on the adaptation option “Decision-support systems”

How does the adaptation solution modify risk reduction?

Decision-support systems mitigate key earthquake impacts listed in the Impact Chain, such as human casualties, limited first response or restricted access to intervention sites. By leveraging real-time data, hazard maps, and vulnerability assessments, these systems enable the strategic deployment of emergency forces resources, optimising response efforts.

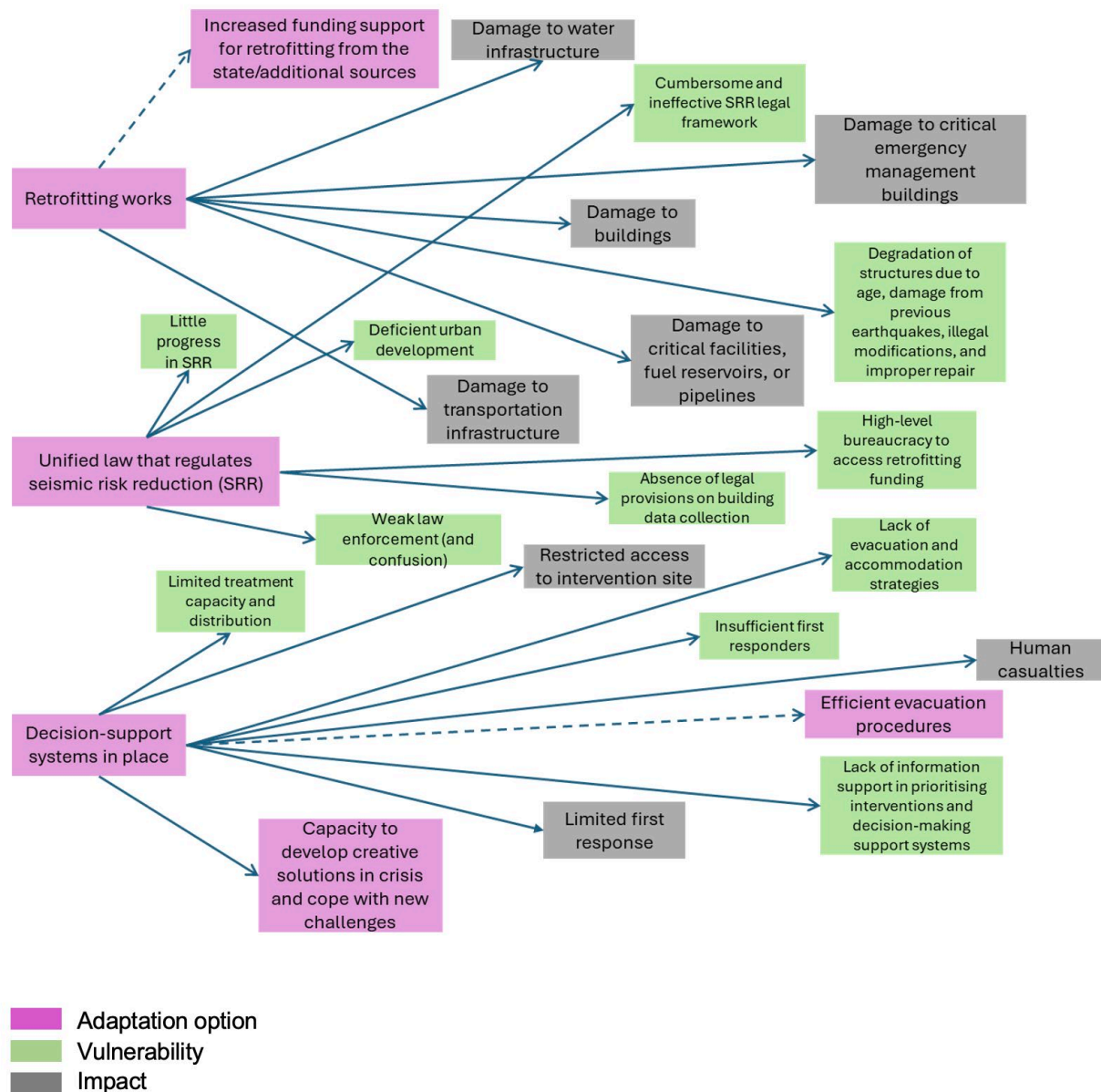


Figure 8 Summary of the selected adaptation options and their effects on impacts and existing vulnerabilities

Furthermore, decision-support systems mitigate institutional vulnerabilities: insufficient first responders; lack of information support in prioritising interventions and decision-making support systems; lack of evacuation and accommodation strategies; limited treatment capacity and distribution. In other words,

decision-support systems enhance earthquake risk management by optimising resource gaps and medical capacity coordination, enabling informed decisions, and strengthening evacuation planning.

Can they be represented by maps?

The decision-support systems cannot be depicted using maps, but their most useful outputs are the spatial representations of emergency interventions. These systems are capable of delineating the service areas of critical emergency management facilities (e.g., hospitals, firefighter units) and identifying the most efficient intervention routes between such facilities and intervention points (e.g., collapsed or damaged buildings, fire locations, road accidents, etc.)

Such systems are the outcome of transdisciplinary research efforts that integrate advanced technologies, requiring considerable financial investment and time. Despite these demands, their primary advantage lies in their significant and lasting contribution to enhanced Disaster Risk Management, which extends well beyond the duration of the lifetime of the project.

3.3 ISTANBUL CASE STUDY OVERVIEW

The megacity Istanbul is located on the western edge of the North Anatolian Fault, making it highly susceptible to earthquakes. With a population exceeding 15 million, the city faces considerable seismic risk. Moreover, Istanbul continues to grow rapidly as a hub of commerce, tourism, and culture, which further increases its exposure to potential hazards. In recent decades, Istanbul has experienced a disproportionate rate of urban expansion compared to its population growth. The city's built-up area expanded by 1.72 times, whereas the population increased by only 1.39 times, highlighting a spatial growth that outpaces demographic trends (Atlas of Urban Expansion, 2023). Alongside this growth, efforts to mitigate the impacts of a potential earthquake have also steadily increased. The two major earthquakes that struck Kocaeli and Düzce Provinces in 1999, in close proximity to Istanbul, acted as a wake-up call and significantly accelerated disaster risk reduction initiatives in the city. Following the Istanbul Province Disaster Prevention/Mitigation Basic Plan Study Including Seismic Micro zoning conducted by the Japan International Cooperation Agency (JICA) and Istanbul Metropolitan Municipality (IMM) in 2002 and the development of the Istanbul Earthquake Master Plan in 2003—prepared by researchers from four major universities—geological assessment and analysis were identified as critical priorities for the city.

Since the devastating earthquakes of 1999 in Kocaeli and Düzce, a wide range of research and practical initiatives have been undertaken in Istanbul to reduce disaster risks (Figure 9). These events served as a critical turning point, raising public awareness and prompting significant institutional responses at both local and national levels. In the aftermath, numerous scientific studies were launched to better understand seismic risks, assess vulnerabilities, and identify potential impacts within the city. Parallel to academic efforts, large-scale urban projects and policy reforms were initiated, including building stock assessments, urban regeneration programs, infrastructure retrofitting, and emergency preparedness planning. Institutional capacities were strengthened, early warning and response systems were improved, and various stakeholder collaborations—including municipalities, universities, NGOs, and international partners—were activated to foster a more resilient urban environment.

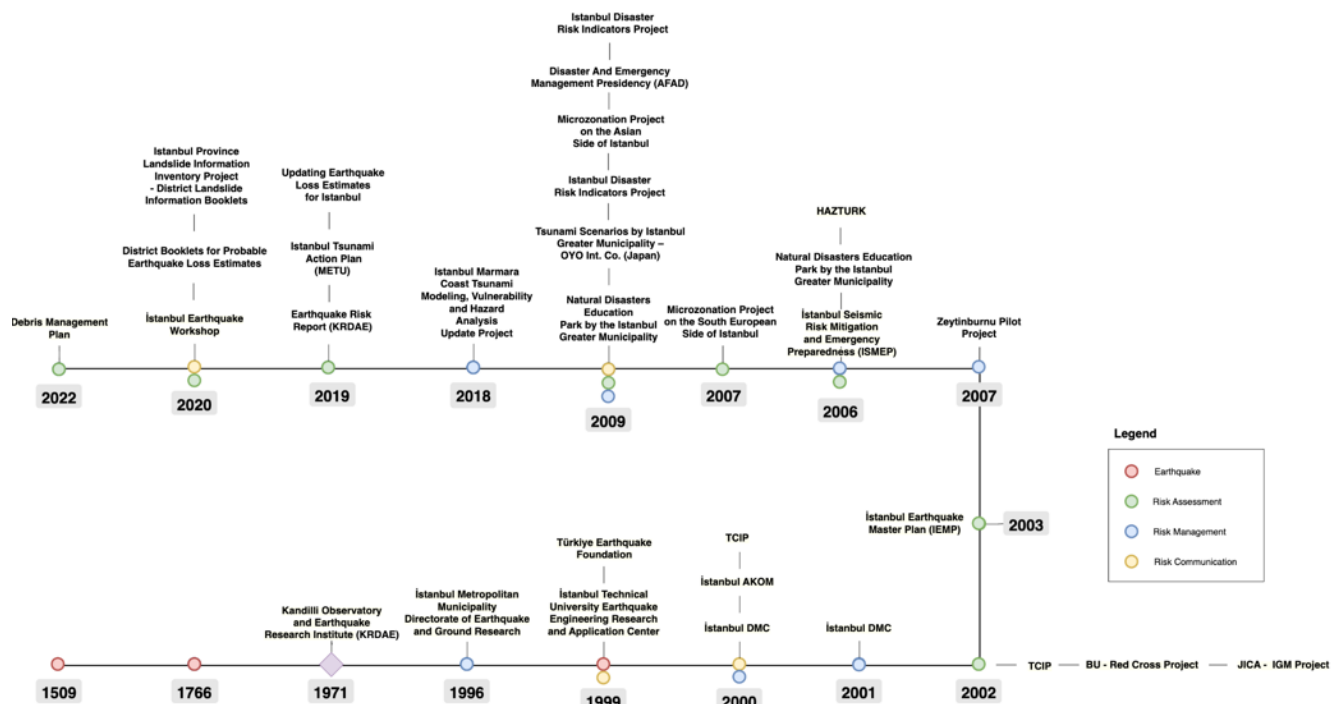


Figure 9 Timeline of Risk Reduction Efforts in Istanbul

In the PARATUS project, we conducted four workshops between June 2023 and June 2025 to examine the systemic risks and sectoral impacts of a potential earthquake exceeding Mw 7.0 along the North Anatolian Fault. With the active participation of over 400 stakeholders representing diverse institutions and sectors, both the temporal and spatial dimensions of seismic risk in Istanbul were thoroughly assessed (Kundak et al., 2024; Kundak et al., 2025). Throughout the workshops, participants collaboratively developed adaptation solutions to address the identified risks. These proposed measures have been aligned with current regulatory frameworks and implementation strategies. A recurring theme emphasised by participants was the critical importance of robust monitoring and control mechanisms to ensure the effectiveness of these solutions. Accordingly, in this chapter, we focus on three adaptation solutions that were most frequently highlighted during the workshops and were also endorsed by the Istanbul Metropolitan Municipality (IMM) as key components of their risk mitigation agenda.

3.3.1 DYNAMIC INTEGRATED RISK ASSESSMENT

In disaster-prone megacities, one of the key challenges in reducing disaster-related damage is the inability to clearly identify and prioritise risks, which hinders effective decision-making by managers and policymakers. Consequently, disaster risk reduction efforts require robust tools and decision support mechanisms that minimise uncertainty and help define priorities more accurately.

The Mega City Indicator System (IMM, 2012) was developed to address this need by providing a structured framework to support decision-makers in formulating effective strategies for disaster prevention and risk management. This system not only facilitates decision-making but also enables comprehensive communication of risk-related information among all stakeholders involved in disaster risk governance.

Moreover, it offers a means to validate disaster prevention policies and investments in a transparent and systematic manner. The model supports analyses by providing results in a clear, user-friendly format, utilising GIS technology to enhance the model's ease of use and application.

The Mega City Indicator System is composed of three key components (Figure 10):

- **Urban Seismic Risk Index (USRI):** Assesses physical risks and social vulnerabilities across urban areas. Physical risk analysis focuses on potential physical losses resulting from an earthquake, including building damage and casualties. Social vulnerability analysis examines how factors such as education, health, economic status, and disaster awareness can exacerbate the impact of these physical losses.
- **Response Capacity Index (RCI):** Evaluates the institutional and operational capacity of the Istanbul Metropolitan Municipality (IMM) to respond effectively to post-earthquake emergencies.
- **Performance-Based Management Monitoring Process (PBMMP):** Measures the performance of IMM in disaster risk management activities using predefined indicators and criteria.

Physical risk data were generated using the Earthquake Loss Estimation Routine (ELER) software, developed by Kandilli Observatory as part of the EU FP6 NERIES project (Mentese et al., 2016). The numerical outputs were digitised and visualised using ArcGIS, enabling spatial representation and analysis of earthquake-related risks across Istanbul (Figure 11). To assess social vulnerability, a large-scale survey was designed at the household level and conducted at the neighbourhood scale, covering the entire metropolitan area. The fieldwork involved the implementation of a structured questionnaire in 955 neighbourhoods, reaching 41,093 households and representing a total of 139,688 individuals. The survey consisted of 78 questions, carefully formulated to capture a broad range of socioeconomic, demographic, and contextual indicators relevant to vulnerability (Figure 12). This comprehensive approach aimed to map the unique social vulnerability profile of each neighbourhood in Istanbul, providing a robust foundation for integrated seismic risk analysis that combines both physical and social dimensions (Figure 13).

As of 2012, a summary of indicator-based assessments using existing datasets was made publicly available. By 2020, the Urban Seismic Risk Index had been partially updated and utilised as a foundational tool for prioritising urban transformation projects aimed at earthquake risk mitigation. Further refinement of seismic loss estimations—including sector-specific assessments (e.g., industrial zones, cultural heritage assets)—is ongoing, integrating updated inventory data and recent scientific advancements. Simultaneously, work continues on updating the Response Capacity Index and the Performance-Based Management Monitoring Process, aiming to provide a more comprehensive and up-to-date framework for evaluating and enhancing the city's disaster resilience.

While the model effectively illustrates the spatial distribution of risk categories across Istanbul, some limitations and challenges remain. Given the city's vast geographic extent and high levels of exposure, more detailed, localised analyses are necessary to enhance the precision and applicability of the findings.

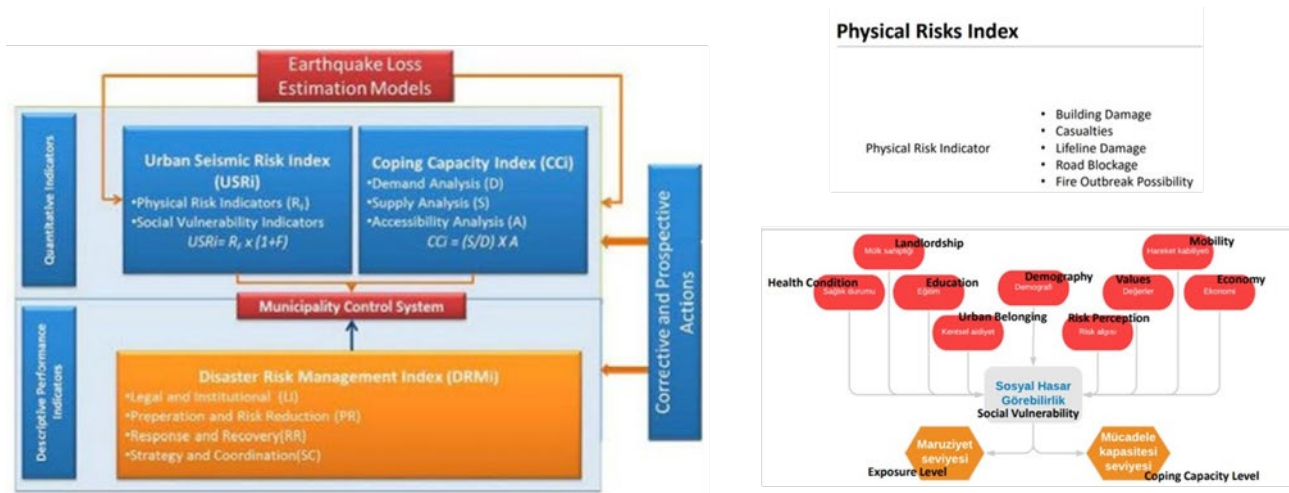


Figure 10 Conceptual model for Mega City Indicator System (MegaIST) showing how Urban Seismic Risk Index (USRI), CCI and DRMI models combined together.

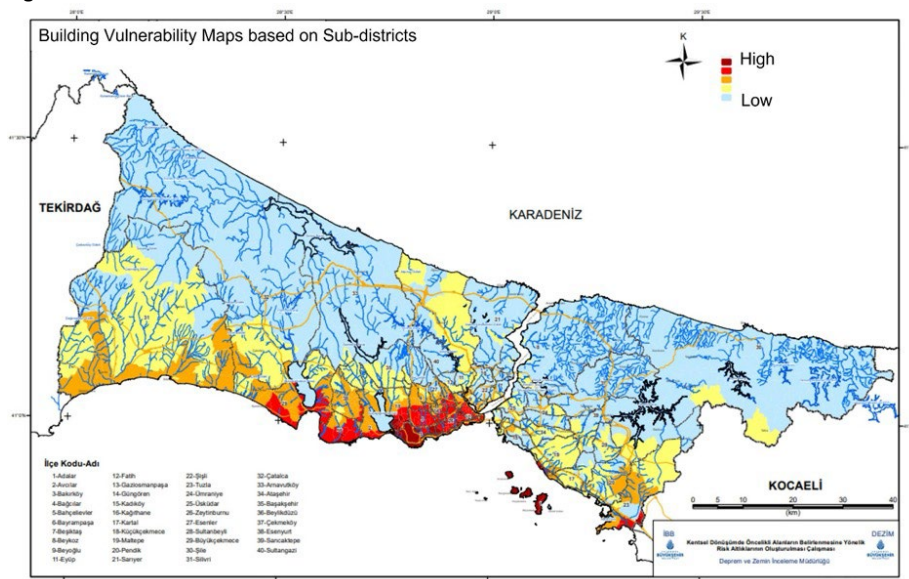


Figure 11 Building Vulnerability Maps based on Sub-districts

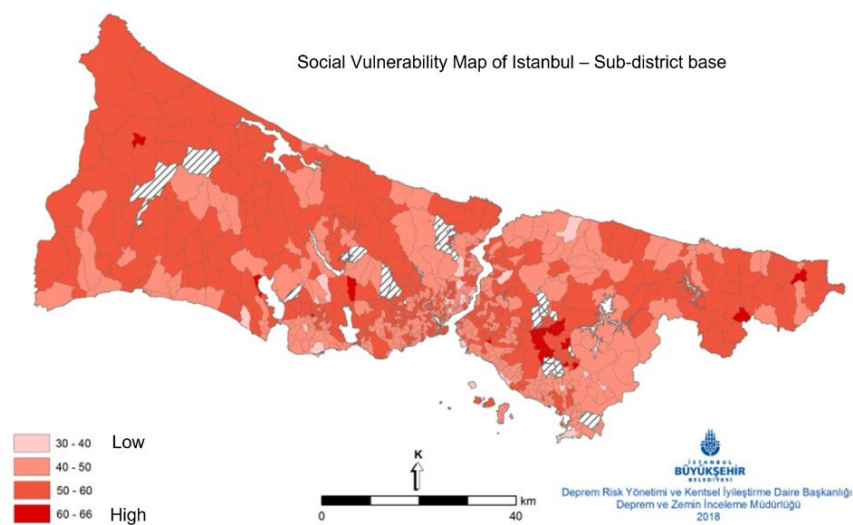


Figure 12 Social Vulnerability Map of Istanbul – Sub-district base

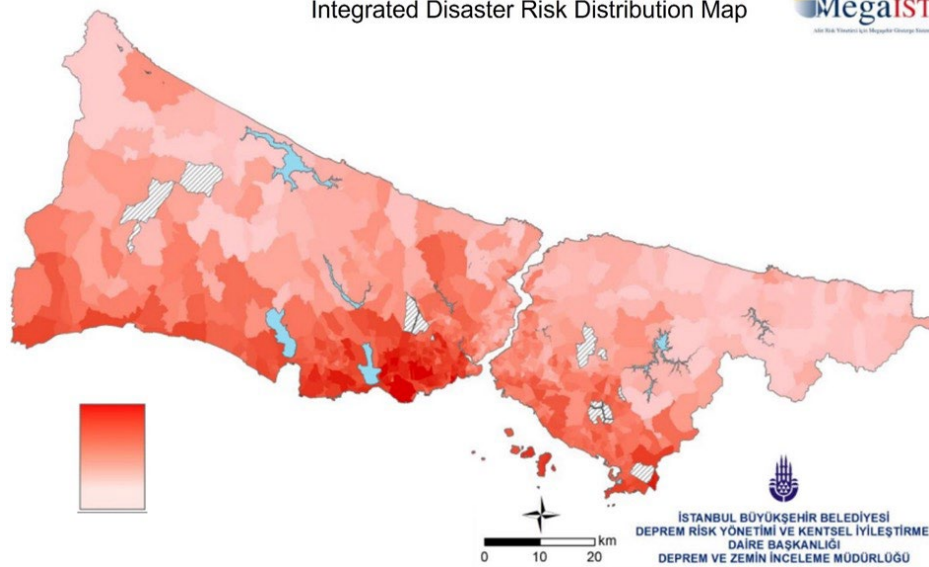


Figure 13 Integrated Disaster Risk Distribution Map of Istanbul

Limitations and challenges

One of the key challenges is the dynamic nature of urban systems, constant changes in the built environment, population composition, infrastructure, and social conditions, which require the risk data to be regularly updated. Static data layers may quickly become outdated, reducing the reliability of risk assessments over time. Furthermore, the integration of physical and social risk dimensions calls for continuous data validation, improved inter-institutional coordination, and robust monitoring mechanisms. The sustainability of the model depends not only on technical improvements but also on the institutional capacity to maintain and update the system, ensure stakeholder engagement, and integrate outputs into planning and decision-making processes.

Despite these challenges, the model serves as a valuable tool for identifying priority areas, guiding disaster risk reduction strategies, and promoting resilience-based urban development. Future efforts should focus on enhancing data resolution, expanding real-time monitoring capabilities, and reinforcing institutional ownership to ensure long-term impact and relevance.

Impact Chain, before and after the implementation

The impact chain developed for Istanbul provides a systems-oriented framework for identifying the causal relationships between vulnerabilities, direct and indirect impacts, and potential adaptation measures. The left-hand panel of the diagram presents a detailed structure of urban risk, with nodes representing hazards, vulnerabilities, impacts and adaptation options linked through directional relationships indicating mitigation potential. A key feature of this framework is the integration of **Dynamic Integrated Risk Assessment (DIRA)** as a high-leverage adaptation solution, as indicated in the Megalst Project. Highlighted on the right-hand side of the figure, DIRA is shown to address a set of six critical vulnerabilities that emerged consistently across stakeholder consultations and technical analyses (Figure 14). These include:

- Unplanned development
- Old building stock
- Mis-implementation of building codes
- Wrong location choice
- Vulnerability by age and disabilities
- Household poverty and unemployment

Each of these vulnerabilities contributes significantly to Istanbul's seismic risk profile, either by increasing exposure to physical hazards or by exacerbating the capacity gaps in response and recovery.

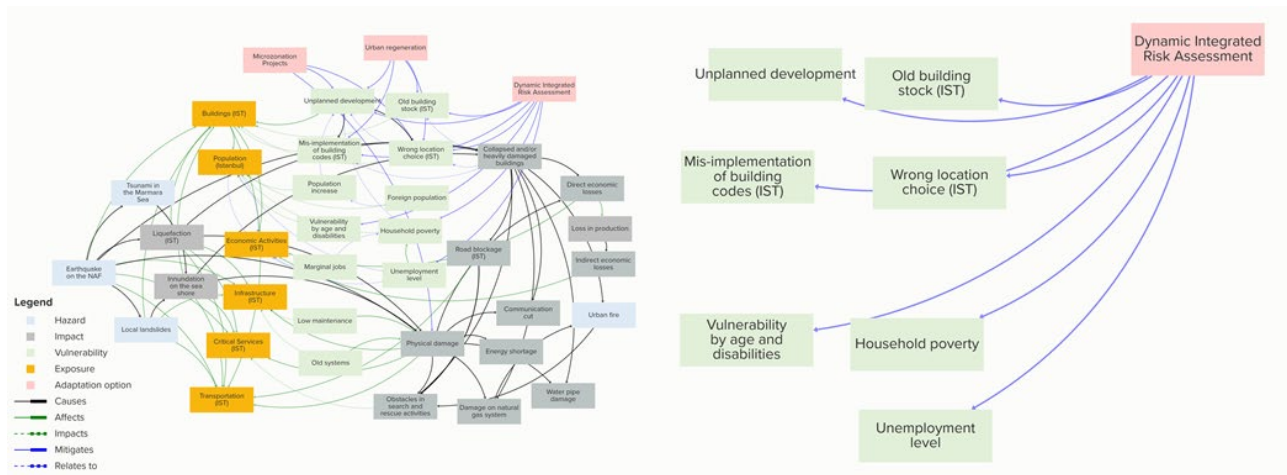


Figure 14 The adaptation efficiency of dynamic integrated risk assessment

How does the adaptation solution modify risk reduction?

DIRA is designed as a continuously updated decision-support mechanism that integrates real-time and longitudinal data related to urban development, infrastructure condition, socio-demographic dynamics, and institutional capacity. Its implementation allows for:

- **Spatial monitoring** of informal or risk-prone urban growth
- **Prioritisation of retrofitting** and mitigation based on the structural condition of buildings
- **Linking socio-economic indicators** (e.g., poverty, unemployment) to disaster preparedness and response planning
- **Enhancement of code enforcement** by connecting inspection outcomes to regulatory revisions
- **Support for inclusive planning** through the incorporation of data on age-related and disability-related vulnerabilities

The systemic influence of DIRA is illustrated by multiple causal pathways in the impact chain towards this single adaptation node. Rather than functioning as an isolated technical tool, DIRA operates as an institutional interface bridging planning, social policy, emergency management, and land use regulation. This systemic positioning makes DIRA a strategic entry point for **prioritising investments, streamlining risk**

governance, and achieving cross-sectoral resilience benefits. Some policy implications and recommendations are summarised as follows:

- DIRA, under the leadership of a metropolitan-level authority, can ensure cross-departmental data flow and decision coherence.
- Pilot implementations in districts with contrasting socio-spatial profiles would provide practical insights into scalability and localisation.
- Developing a monitoring dashboard linked to key performance indicators (KPIs) for each addressed vulnerability would enable effective tracking of progress and impact.
- Regular training of municipal planners, building inspectors, and community-level actors would support the operational use of the system.

The Istanbul impact chain demonstrates that systemic urban risks cannot be addressed through fragmented interventions. The DIRA framework offers a coherent, adaptive, and data-driven approach to urban resilience, capable of aligning long-term planning with near-term action and continuous learning.

Can they be represented by maps?

The vulnerabilities, risks, and adaptation measures presented in the Istanbul impact chain can be effectively represented through thematic and composite maps. In fact, spatial representation is a fundamental component of the DIRA framework, as it enables both decision-makers and local stakeholders to visualise the distribution, concentration, and evolution of risk factors across the metropolitan area. Many of the key vulnerabilities highlighted, such as unplanned development, old building stock, poverty, misapplication of building codes, and location-based exposure, are inherently spatial phenomena. These can be mapped using existing spatial data, land use inventories, building age and condition databases, socioeconomic indicators at the neighbourhood scale, and updated hazard models. By integrating such spatial products, the impact chain model transitions from a conceptual framework into an operational risk governance tool. Ultimately, maps serve not only as communication instruments but also as analytical platforms for developing evidence-based, place-specific, and equity-oriented disaster risk reduction strategies.

3.3.2 URBAN REGENERATION

The Urban Transformation Law (Law No. 6306 on the Transformation of Areas Under Disaster Risk) was published in the *Official Gazette* on 31 May 2012. The main goal of the law is to reduce earthquake-related risks by allowing the state to identify “risky structures” or “risky areas,” and to carry out demolition and reconstruction through agreements with property owners or, when necessary, expropriation. It also provides financial support and incentives for these processes. In practice, Law No. 6306 plays a significant role in Türkiye’s urban resilience strategies. While pilot projects in earthquake-prone districts of Istanbul have combined structural improvements with redevelopment incentives, ongoing legal disputes and concerns from local communities highlight the need for stronger social protection measures.

This section presents a recent urban regeneration project implemented by the Istanbul Metropolitan Municipality (IMM) in the Bayrampaşa district as an example of disaster risk reduction in action. The project

involved relocating residents of the İsmetpaşa neighbourhood to a newly built residential complex, Güneşli Residences, located on the site of the former Bayrampaşa Prison, an area designated as a reserve zone in 2013. The relocation process began in 2020 with the formation of a dedicated site management team. In January 2022, a major step was taken when the construction license and occupancy permit were renewed. By September 2022, condominium status had been granted, and 2,473 independent housing units were officially registered. The first title deeds were issued on 18 September 2023. Stakeholder participation in the project has been strong. As of now, 91% of the rightful owners have reached agreements with the municipality. So far, 387 apartments have been transferred to their new owners, and the remaining transfers are continuing rapidly. In addition, 211 privately owned structures in the original neighbourhood have been demolished as part of the transformation, and construction in the associated commercial areas is ongoing (Figure 15).

Most recently, on 11 July 2024, the IMM Assembly approved the temporary allocation of Güneşli Residences to eligible beneficiaries, representing another important milestone in the city's ongoing efforts to reduce disaster risk through planned urban regeneration.



Figure 15 Allocation of Temporary Housing in Bayrampaşa İsmetpaşa Neighbourhood

Limitations and challenges

Scholars view this legislation as part of a broader shift in Turkey's urban policy, from a market-oriented redevelopment model toward one that emphasises disaster risk reduction. Güzey (2016) explains that, following the 1999 Marmara earthquakes, urban regeneration began to be framed as a state-led strategy for hazard prevention, setting the stage for the enactment of Law No. 6306. The law introduced a range of financial instruments, such as Treasury-backed loans and rent support, as well as streamlined planning procedures to accelerate the replacement of vulnerable buildings. However, the implementation of the law has been widely debated. Early empirical research on Istanbul's renewal projects suggests that state-led regeneration often results in large-scale property transfers, favouring investors at the expense of existing residents (Kuyucu & Ünsal, 2010). Later critiques point out that forced acquisitions and the limited involvement of affected communities can deepen social inequalities and lead to displacement (Demirdağ, Erçetin & Durmaz, 2023). From a resilience planning perspective, Eraydin and Taşan-Kok (2013) argue that risk governance should go beyond physical safety and include inclusive, community-based approaches.

In practice, Istanbul's urban regeneration efforts, primarily designed to reduce seismic risk, have considerably increased the formal housing stock. By raising floor-area ratios and allowing for higher residential densities within project zones, these programs have added a large number of new housing units to the city. However, the resulting market dynamics often conflict with broader social policy goals. Many of the newly built units are treated as investment assets, which limits their availability to households in need of affordable housing. According to the Istanbul Planning Agency (IPA), as of 2020, the city had approximately 6.4 million housing units, of which 1.8 million were unoccupied (IPA, 2021). While some of these empty units serve as seasonal or secondary homes, spatial analysis shows that a significant portion is located in large-scale housing developments on the urban fringe. As a result, although regeneration contributes to safer building stock and increases overall supply, it has yet to resolve the issue of housing affordability. A considerable share of new or vacated units remains inaccessible to low- and middle-income households, highlighting the need for supporting policies, such as inclusionary zoning, rental regulation, or targeted subsidies, to ensure that seismic risk reduction also leads to more equitable housing outcomes.

Impact Chain, before and after the implementation

The impact-chain diagram conceptualises urban regeneration as a key adaptation solution that addresses four critical vulnerabilities within Istanbul's seismic risk landscape: unplanned development, outdated building stock, misapplication of building codes, and inappropriate site selection. These vulnerabilities hold central positions in the left-hand portion of the diagram, acting as major conduits through which a severe seismic hazard is transmitted into a wide array of exposures and cascading impacts, including structural failure, business interruption, disruption of essential services, and secondary hazards such as urban fires (Figure 16). Because these four vulnerabilities function as key intersections within the network, targeted interventions in these areas can produce multiplicative benefits in terms of risk reduction. In practical terms, addressing these vulnerabilities through urban regeneration results in a chain of positive outcomes: fewer buildings are likely to collapse, which in turn means less damage to critical infrastructure, fewer disruptions to economic activities, and ultimately, reduced harm to social systems and livelihoods. This cumulative effect demonstrates the systemic value of regeneration when implemented strategically.

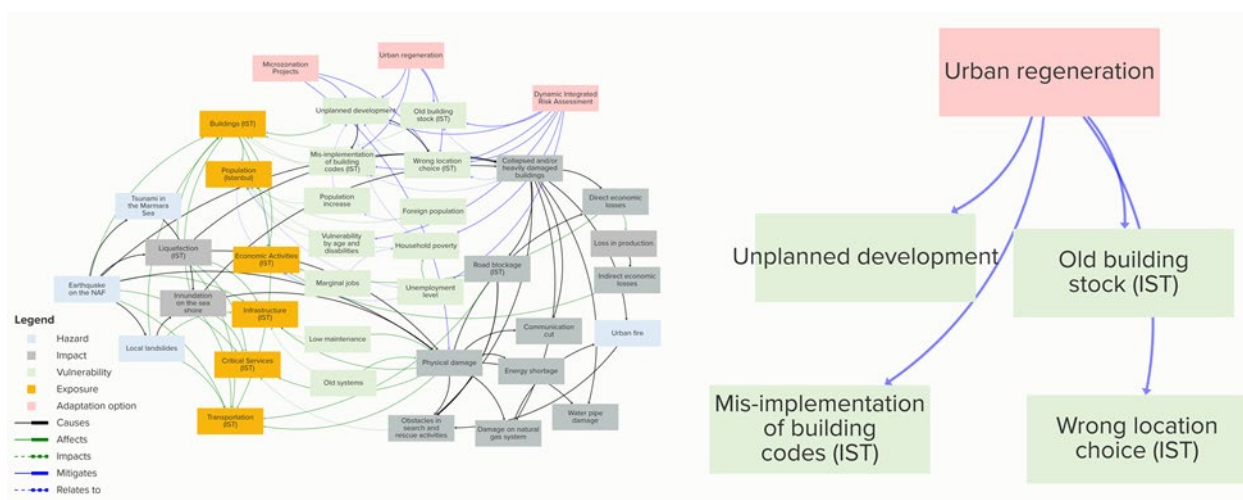


Figure 16 The adaptation efficiency of urban regeneration

How does the adaptation solution modify risk reduction?

Urban regeneration, as conceptualised in the Istanbul impact-chain model, contributes to disaster risk reduction by directly addressing key vulnerabilities that amplify the consequences of a major seismic event. Rather than operating as an isolated physical intervention, regeneration modifies the structure of urban risk through multi-dimensional processes of spatial planning, structural renewal, regulatory enforcement, and socio-spatial restructuring.

By targeting critical vulnerabilities such as unplanned development, old building stock, mis-implementation of building codes, and poor location choices, regeneration disrupts the causal pathways that would otherwise lead from a seismic hazard to cascading social, physical, and economic impacts. The demolition of structurally unsafe buildings and their replacement with code-compliant, seismically resilient units significantly reduces the probability of collapse, injury, and death. In addition, the reconfiguration of formerly informal or hazard-prone areas not only decreases physical exposure but also improves access to infrastructure and emergency services, thereby mitigating secondary risks such as road blockage, fire outbreaks, and disruption of critical lifelines.

In summary, urban regeneration modifies risk by restructuring both the built environment and the institutional processes that govern urban growth. It reduces seismic vulnerability through safer construction, limits exposure by relocating residents away from high-risk zones, and creates a platform for more accountable and adaptive risk governance.

Can they be represented by maps?

Urban regeneration areas, whether completed, ongoing, or planned, can currently be represented at the scale of Istanbul primarily as point data. This is due to limitations in spatial resolution and the availability of publicly available datasets at the metropolitan level. While such point-based representations are useful for visualising the distribution of regeneration efforts across the city, they do not fully capture the spatial extent or morphological characteristics of the interventions.

At smaller spatial scales, particularly in district-level or neighbourhood-level maps, it becomes possible to depict these areas in greater detail. In such cases, regeneration zones can be represented as polygons,

allowing for more accurate analysis of their relationship to local vulnerabilities, land-use patterns, and hazard zones. This finer resolution enables planners and researchers to better assess the spatial effectiveness of regeneration as a risk-reduction strategy and to integrate it into localised disaster mitigation and resilience planning efforts. However, certain details regarding these projects cannot be shared with the public to protect personal and commercial rights but may be shared with institutions that have roles and responsibilities in the planning process.

3.3.3 MICROZONATION PROJECTS

Microzonation studies represent a foundational component of Istanbul's earthquake risk reduction strategy, offering location-specific insights into seismic hazards that go beyond the scope of traditional regional zoning approaches. The first microzonation efforts in Istanbul began in 2002; building on this early work, the Istanbul Metropolitan Municipality's (IMM) Directorate of Earthquake and Ground Research expanded the research with two studies; on the European Side in 2007 and the Asian Side in 2009 covering a total of 692 km² of urbanised territory (IMM, 2007; IMM, 2009). These studies integrated interdisciplinary and multi-hazard methodologies to develop risk-oriented spatial datasets that now serve as essential inputs in a broad range of urban development and planning processes.

The outputs of these microzonation efforts are applied across multiple domains of urban governance. They are systematically embedded in land-use and development plans, inform hazard identification and mitigation in urban regeneration projects, and support the selection of safe corridors and design parameters for large-scale engineering infrastructure, including highways, tunnels, bridges, railways, viaducts, and port facilities. By basing these decisions on detailed and site-specific geo-scientific evidence, the IMM ensures that future growth is aligned with the principles of earthquake-resilient urbanisation.

As visualised in Figure 17, the microzonation workflow follows a multi-stage, data-integrated approach. Initially, geophysical, geological, topographical, and hydrological data are collected and analysed to produce individual hazard layers, such as liquefaction susceptibility (Figure 18), landslide risk (Figure 19), tsunami hazard map (Figure 20), flooding potential (Figure 21), earthquake hazard map (Figure 22) and geological map (Figure 23). These layers are then synthesised into a composite land-suitability map, which categorises all urban areas according to their relative appropriateness for development, restriction, or site-specific mitigation strategies (Figure 24).

Importantly, the land-suitability map output is not just an analytical tool; it holds regulatory status in spatial planning processes. It functions as an obligatory reference layer for development control and risk-sensitive urban decision-making. In this sense, microzonation plays a dual role: it strengthens scientific risk assessment while simultaneously enabling its operationalisation within planning practice. Through this approach, the IMM has institutionalised a science-to-policy translation mechanism, ensuring that risk-informed strategies are not only developed but also consistently implemented in urban expansion, infrastructure development, and regeneration initiatives. As Istanbul continues to grow under the persistent threat of a major earthquake, microzonation remains a cornerstone of its proactive resilience planning framework.

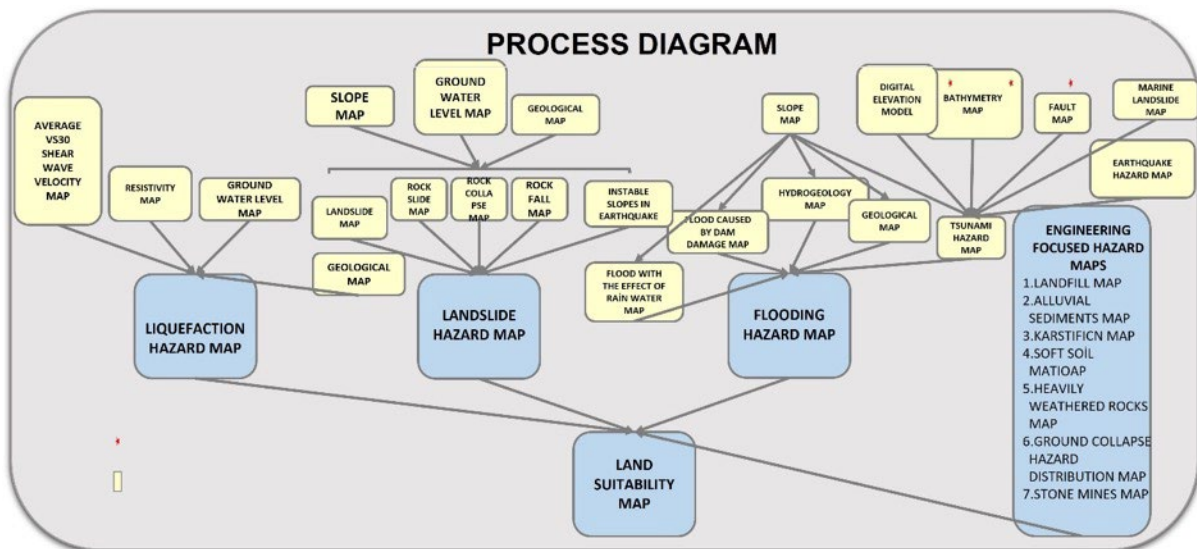


Figure 17 Process diagram of interdisciplinary multi-hazard risk analyses



Figure 18 Liquefaction Hazard Map

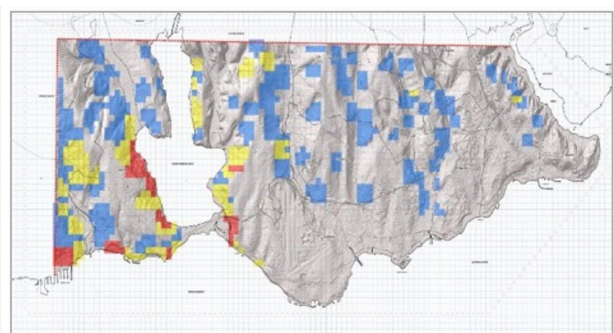


Figure 19 Landslide Hazard Map

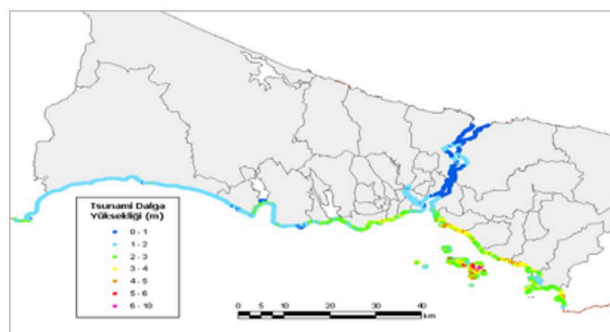


Figure 20 Tsunami Hazard Map

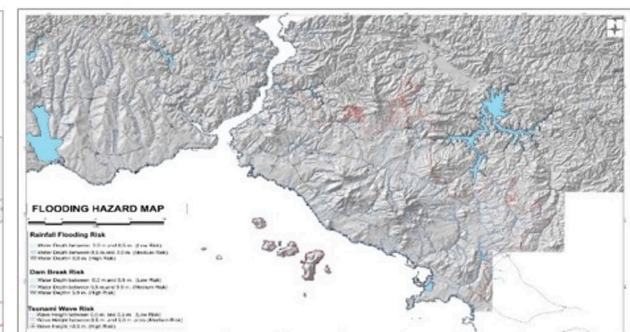


Figure 21 Flooding Hazard Map

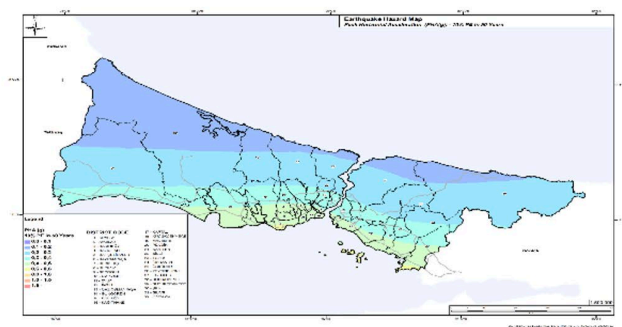


Figure 22 Earthquake Hazard Map

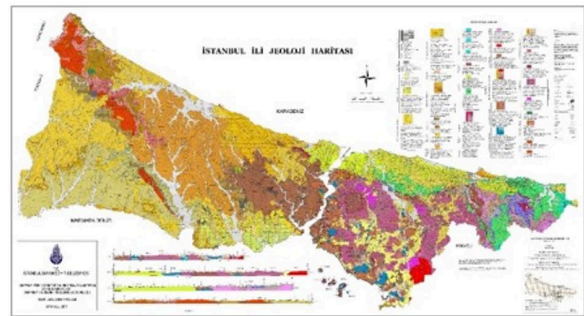


Figure 23 Geology Map

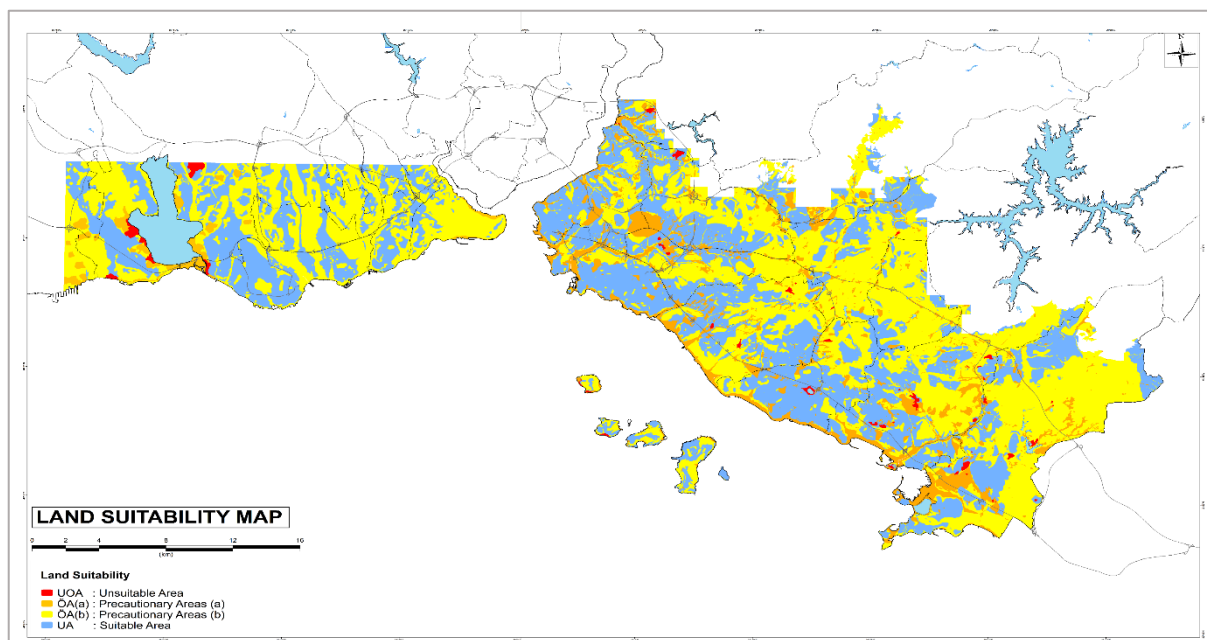


Figure 24 Land Suitability Map

Limitations and challenges

Although Istanbul's microzonation program has made considerable progress, notable gaps remain, particularly across the metropolitan fringe, where suburban expansion and informal development are accelerating. These unmapped peripheral zones, often characterised by rapid and unregulated growth, represent critical spatial blind spots in the city's seismic risk landscape. The absence of detailed geo-scientific data in these areas constrains the municipality's ability to design and implement a truly comprehensive, risk-informed land-use policy.

The most significant barrier to expanding coverage is financial. High-resolution microzonation studies require intensive fieldwork—including borehole drilling, geophysical surveys, and in-situ dynamic testing—as well as advanced laboratory analyses and numerical modelling techniques. These components demand substantial investment, and current funding levels are insufficient to scale the survey density needed for full metropolitan coverage.

Impact Chain, before and after the implementation

The updated impact chain diagram highlights microzonation projects as a proactive adaptation measure that intervenes early in the sequence connecting a severe earthquake on the North Anatolian Fault to urban vulnerabilities, particularly unplanned development, inappropriate site selection, and subsequent infrastructure damage (Figure 25).

By providing site-specific information on hazards such as liquefaction, landslides, and flooding, microzonation enables local authorities to regulate land use more effectively. Once these risks are identified, construction permits can be denied or design modifications can be mandated, thus curbing development in unsuitable areas. In this way, wrong location choices are largely avoided, as land-use plans must reference microzonation data before zoning or allocation decisions are finalised.

As illustrated by the mitigation pathways in the diagram, weakening these upstream vulnerabilities significantly reduces the likelihood of severe infrastructure impacts. Rather than reinforcing individual buildings, microzonation acts as a spatial filter, steering development away from high-risk zones and promoting safer urban growth patterns. This early-stage intervention helps to decrease the progression from seismic hazard to physical loss, making it a critical tool in earthquake risk reduction.

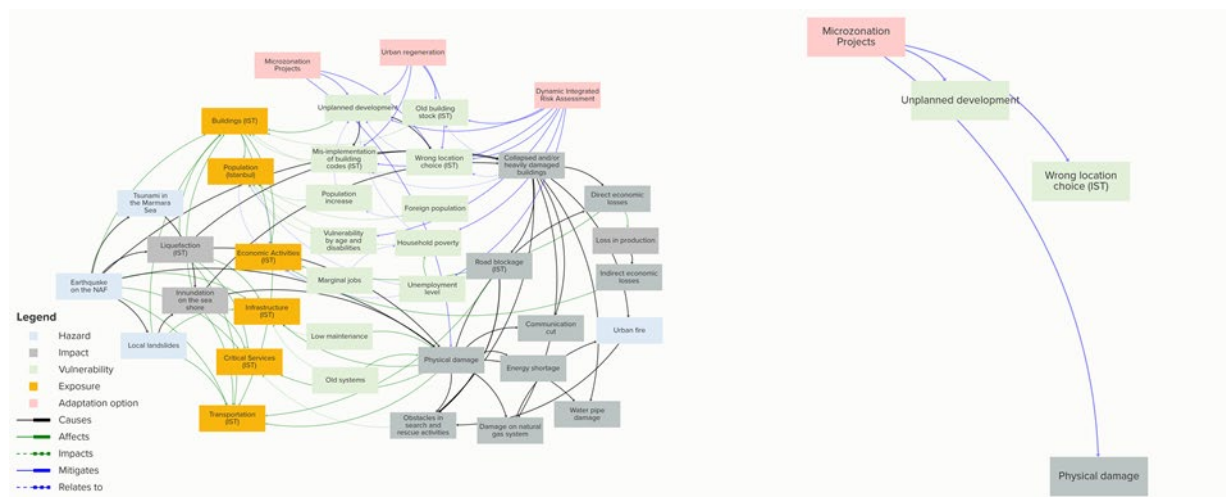


Figure 25 The adaptation efficiency of microzonation projects

How does the adaptation solution modify risk reduction?

Microzonation projects significantly transform Istanbul's earthquake risk landscape by integrating detailed geoscientific data into urban planning processes. These studies translate broad regional hazard assessments into parcel-scale suitability maps, providing planners with a solid foundation to restrict development or enforce structural precautions in areas vulnerable to liquefaction, landslides, or flooding.

By intervening early, before land is allocated or construction begins, microzonation targets two critical vulnerabilities: unplanned development and inappropriate site selection. This early-stage risk governance mechanism helps reduce exposure by diverting new construction away from unstable ground and decreases vulnerability by ensuring that approved developments account for local seismic conditions. In doing so,

microzonation effectively interrupts the causal chain that would otherwise link a major earthquake on the North Anatolian Fault to extensive physical damage. It prevents risky building practices, protects vital infrastructure corridors, and helps keep emergency-access routes functional after a disaster.

While microzonation does not address existing vulnerabilities in the current building stock, it plays a crucial role in shaping safer patterns of future urban growth. However, for this approach to reach its full potential, remaining coverage gaps must be addressed, regular updates must be funded, and enforcement practices must remain consistent with evolving hazard maps.

Can they be represented by maps?

Microzonation projects are not only representable through maps; rather, they are inherently map-based decision-support tools. The primary objective of microzonation is to transform geological, geotechnical, and geophysical data into spatially explicit hazard layers, such as liquefaction susceptibility, landslide probability, and flood potential, that can be visualised, interpreted, and applied across various planning domains. Produced at high spatial resolution, these hazard maps serve as essential inputs for urban development and land-use planning. They guide planners and engineers in identifying areas where construction should be restricted, where additional structural safeguards are required, and where development may proceed with minimal risk. In this way, microzonation outputs help to reshape the spatial organisation of urban growth by delineating both risk zones and safe areas.

3.3.4 ISTANBUL CASE STUDY CONCLUSION

When examined through the lens of the impact chain diagram, it becomes evident that the adaptation solutions associated with the highest number of impact linkages are also those most frequently emphasised during the stakeholder workshops and prioritised by the IMM. This convergence suggests a strong alignment between systemic risk pathways identified analytically and the practical priorities recognised by both local authorities and multi-sectoral participants. It also underscores the relevance and strategic value of these adaptation measures in addressing Istanbul's most critical vulnerabilities. Consequently, **DIRA**, **urban regeneration**, and **microzonation** stand out as complementary tools that together reshape the city's capacity to anticipate, absorb, and adapt to seismic threats.

DIRA serves as a multidimensional risk-governance framework that links physical vulnerabilities, institutional response capacity, and performance monitoring through a structured set of urban risk indicators. By translating complex risk factors into actionable metrics, it supports informed decision-making and promotes transparency and accountability in disaster planning.

Urban regeneration, on the other hand, provides a tangible mechanism to reduce the vulnerability of the built environment. Through the replacement of unsafe buildings, these projects address structural weaknesses, mitigate cascading failures, and increase housing resilience. However, the long-term success of regeneration also depends on social equity and affordability, highlighting the importance of integrating inclusive planning and policy safeguards.

Microzonation complements these efforts by embedding high-resolution geo-scientific knowledge into the early stages of land-use planning. Its map-based outputs enable the precise identification of areas unsuitable

for development, thereby preventing future exposure and shaping safer urban expansion. By guiding development away from high-hazard zones and toward safer ground, microzonation acts as a spatial filter that minimises future vulnerability.

Together, these three adaptation strategies form a layered and mutually reinforcing approach to disaster risk reduction in Istanbul. While DIRA builds institutional foresight and capacity, urban regeneration enhances the physical robustness of the housing stock, and microzonation ensures that new development adheres to site-specific safety parameters. When applied in coordination, these tools transition the city from reactive responses to a proactive, systemic, and spatially informed risk governance model, one that not only protects lives and assets but also promotes sustainable and resilient urban growth.

3.4 ALPS CASE STUDY OVERVIEW

The application site Alps faces a spectrum of hazards, ranging from natural events such as landslides, avalanches, rockfalls, and wildfires, to anthropogenic threats including transportation accidents or congestion and overall climate change. A more detailed description of the Case Study area can be found in Deliverables 1.1, 1.3, 6.2, 6.3 and 6.4 as well as in Wenzel et al. (2024). Generally, before focusing on adaptation measures themselves, it is essential to emphasise the importance of climate change mitigation as a base strategy and address synergies between adaptation and risk mitigation measures, as done by Sekhri et al. (2020). Greenhouse gas reduction remains the most effective long-term measure to reduce the occurrence and intensity of many alpine hazards, including extreme precipitation, heatwaves, and ecosystem shifts that exacerbate vulnerabilities (IPCC, 2022). This is particularly concerning as projections suggest that a 2°C regional warming could lead to a doubling of 50-year rainfall events across the Alps, with the highest increases occurring at high-elevation stations (Peleg et al. 2025).

Adaptation in this complex multi-hazard environment must therefore be flexible, encompassing both structural and non-structural strategies and be based on methods that can account for multi-risk situations (Terzi et al. 2019). We also need to consider long-term and short-term adaptation measures that can reduce, e.g. exposed assets. Combined mobility strategies (multimodality) - e.g. promoting robust transport chains by integrating bus, rail or even bicycle options can be an alternative in the event of an incident, or to generally reduce the amount of exposed assets. Also, general cross-border knowledge transfer and collaboration between alpine areas, for unified responses to shared risks, can be an effective strategy. All around Europe and within Austria, cell broadcasting starts to become standard for disaster warning and could be a way forward for instructional alerting for multi-hazard, risk scenarios, providing not only hazard warnings but actionable guidance for populations at risk (e.g., evacuation routes, shelter-in-place orders). The diverse range of hazards in the Alpine application site requires a multi-layered adaptation approach that combines engineering solutions, ecosystem-based nature-based solutions (NBS), and behavioural strategies such as multi-hazard risk (MHR) communication. It is also evident that these measures cannot be implemented solely at the local level; instead, they demand cross-scale collaboration. EU-level regulations play a key role in complementing local strategies by fostering system-wide resilience. In the following subchapters, different examples for this application case study are presented.

The Brenner Pass is one of the most vital alpine crossings in Europe, facilitating a large volume of trade between Italy and Northern Europe. A blockage can cause severe traffic congestion at alternative routes, increasing travel times and transportation costs. This disruption can affect supply chains, leading to delays in deliveries and shortages of goods. Additionally, tourism may suffer as travellers face longer detours and delays, potentially discouraging visits to popular Italian destinations. The economic effects can be substantial, impacting businesses and the broader economy, which is reliant on smooth and efficient transit through this key corridor.

Methodology

The impact chain developed for a major landslide-induced disruption integrates a range of adaptation options spanning all phases of the Disaster Risk Management Cycle, preparedness, response, and recovery. It focuses on the transport sector (highway and railway) for South Tyrol and Tyrol, describing the main impacts under the current risk situation. It is based on specific past events as well as on inputs from experts during workshops and expert-based assumptions.

From this comprehensive framework, three representative adaptation options were selected, along with their associated risk mitigation measures. The selection was guided by their relevance across a wide spectrum of potential impacts and vulnerabilities, ensuring broad applicability and strategic value.

These adaptation options were evaluated in relation to the following **scenario**:

A large landslide event causes the complete blockage of a mountain pass highway, leading to major disruptions of traffic. The situation is further exacerbated by disorganised behaviour among some individuals, which impedes the efforts of emergency responders to access and manage the site efficiently. Significant rerouting of traffic leads to cascading effects on nearby transportation networks, including regional roads and railways, which experience severe congestion and temporary overload due to the sudden surge in demand.

3.4.1 PROTECTION MEASURES

Engineering options: Rockfall nets, dams and slope meshes

Nature-based solutions: Slope stabilisation, protection of forests, etc.

Protection measures serve as strategies and actions to reduce or prevent potential damage caused by natural events such as debris flows, rockfalls, avalanches, etc. Here, those will be split into engineering and nature-based solutions.

Engineering solutions

Certain hazards, such as predictable rockfall events, can be addressed through structural engineering solutions, including rockfall nets, slope reinforcements or resilient building design (Holub et al. 2012; ÖNORM B). These solutions are designed based on detailed hazard modelling, including rockfall trajectory simulations

and kinetic energy absorption calculations. Debris Flows, for example, can also be managed with engineering solutions, such as the implementation of check dams, which is also evident in the Brenner corridor.

Nature-based solutions

Nature can be seen as a cost-effective and no-regret solution to reduce risks from natural events and hazards, complementing conventional engineering measures and leading to a greener and environmental friendlier option. Maintaining healthy vegetation and forest ecosystems for example, is a key nature-based solution and mitigation-adaptation synergy (Abernethy & Rutherford 2000; Kraushaar et al. 2018). Forests reduce direct splash erosion, stabilise slopes, provide wind and snow break, reduce the likelihood of avalanches, and offer microclimatic cooling. Similarly, reducing elements at risk contributes to both mitigation and adaptation. Encouraging public transportation, reducing individual travel, and optimising freight logistics decreases exposure to road-related hazards, reduces congestion, and facilitates faster access for emergency services to accidents and local communities.

Italy vs. Austria

Since the case study site for the Alps represents a cross-border region, national differences in the implementation and, in general, in the strategy for adapting to hazards can be observed.

In South Tyrol, the decision-making power lies in the autonomous province, allowing more localised adaptation to hazards and different pathways to implement measures. Examples seen in the case study include the operations centre of the volunteer fire department Pflersch, where the engineering measure has a dual use: a conventional check dam to prevent debris flows from affecting the surrounding areas, as well as a stylish option for the firefighters' house, combining spatial planning and adaptation.

As a counterpart, the Austrian authorities rely more on national laws and regulations, which are then further refined by the federal states after the national regulations. In the last years, especially protection forests have been seen as the major adaptation option next to all the engineering structures.

An overview of some engineering and nature-based protection measures:

- Installation of rockfall and avalanche protection systems (e.g., rockfall nets, rockfall dams, snow sheds, protection forests in the transit area and deflection structures).
- Stabilisation of exposed slopes through revegetation, erosion control blankets, and bioengineering techniques.
- Debris Traps along dedicated debris-pathways, also possible as a series of constructions for high-risk areas – transverse or longitudinal constructions; Retention basins
- Mobile flood protection (inflatable/collapsible barriers that can be temporarily installed)
- Integrating climate change scenarios, such as impact assessment, as a mandatory part of future infrastructure planning/maintenance (e.g. EU-Taxonomie, ASFINAG)

1. *In Austria, protection measures are widely used and implemented across various sectors. For the Brenner, especially along traffic infrastructure (ASFINAG, Federal State, ÖBB), such as highways, and in general near settlement areas (Torrent and Avalanche Control), an implementation took place.*



Figure 26 Rockfall nets



Figure 27 Slope meshes



Figure 28 Rockfall dam embedded in nature check dam

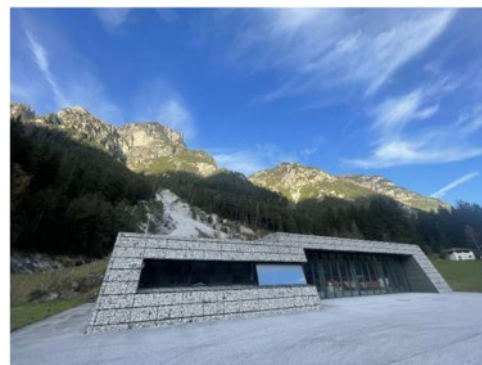


Figure 29 Fire fighter centre in Pflersch

Limitations and challenges

Purely structural measures are highly dependent on engineering calculations; if input parameters change (like return periods due to climate change), these calculations would also need adaptation and could fail. Therefore, planning tools (e.g. hazard zone planning from the Torrent and Avalanche Control) should focus more on future changes rather than current conditions. It is also noted that structural engineering measures are expensive to construct and require regular maintenance.

Additionally, nature-based solutions are also affected by climate change. If for example, weather patterns change and become more localised and extreme, natural slope stabilisation measurements or protection forests are also likely to fail. So, while nature-based approaches can support erosion control, the use for stabilising slopes depends on the type of possible landslides.

Impact Chain for the Alps

The impact chain in the Alps focuses on the transport sector (highway and railway) along the Brenner Pass between Austria and Italy. The impact chain shows clearly key hazards, vulnerability, exposure and impact at the current risk situation of the transport sector connected to the Brenner Pass. The identified adaptation options aim at reducing or preventing damage (using engineering and nature-based solutions), improving the communication and management practices in connection with certain hazards and to monitor possible landslide sites while implementing an early warning system.

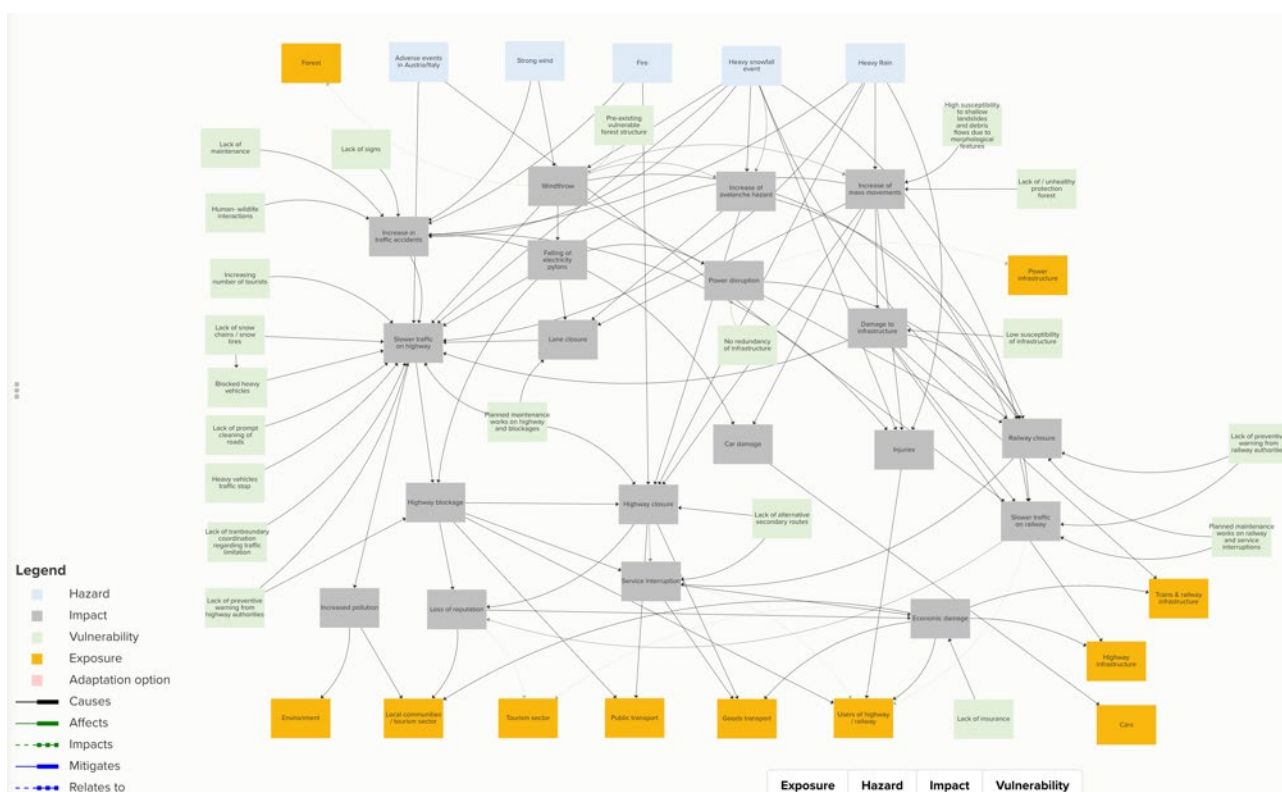


Figure 29 Impact Chain focuses on the transport sector (highway and railway), describing the main impacts under the current risk situation (find the interactive map here: <https://kumu.io/Paratus/alps-case-study#alps-brenner-corridor-application-case-study>)

How does the adaptation solution modify risk reduction?

The possible spatial extent of a hazard can be altered or completely blocked. The spatial extent of a hazard can be altered, and thus the hazard itself can change. Protective structures can be placed in the initial area of certain hazard types to prevent an event from starting (e.g. avalanches). They can also mitigate a hazard by acting as an obstacle (e.g. forests, rockfall net).

Lower vulnerability of traffic infrastructure and settlement area through protection measures can also lead to mal-adaptation, and a false feeling of safety, because even the best structures can fail.

Can they be represented by maps?

Yes, all the protection measures have a specific lifetime expectancy (normally 30 years) and set maintenance costs that need to be considered. However, currently, many protection structures have unknown age and responsibility.

3.4.2 OPERATIONAL ADAPTATIONS

Operational adaptations in the road traffic sector involve a broad spectrum of strategies aimed at responding to disruptions. These may include incidents such as accidents, but also natural hazards like windthrow, debris flows or heavy snowfall. The timely detection of such events and the initiation of preliminary response

measures are already feasible. In the direct aftermath of an event, operational adaptations are not limited to restoring traffic flow but also focus on minimising further impacts. This may include the rapid deployment of temporary barriers or protection systems (e.g. mobile flooding barriers), rerouting traffic to avoid affected sections, conducting immediate safety checks, or increasing patrol frequency in vulnerable areas. Effective cooperation with emergency services is critical to ensuring a coordinated and rapid response.

1. Management practice

From the perspective of traffic operators, the origin of a disruptive event—whether anthropogenic or natural—is secondary. Comparable management procedures are applied in both cases. However, High Impact Low Probability (HILP) events demand additional attention, particularly in the form of robust contingency planning. This includes scenario-based exercises, inter-agency coordination and early recovery strategies. For example, ASFINAG's contingency plan - initially developed for a worst-case scenario of a bridge collapse - can be adapted for natural hazard scenarios with similar impact potential.

2. Communication with road users

An essential element of operational adaptation is the adjustment of control systems to ensure timely communication with road users. Variable message signs are used to provide real-time information, tailored to the nature of the event. These systems are flexible and can be used to convey a wide range of messages - be it a traffic jam, snow clearing operations or an accident - thus enhancing road user awareness and safety.

3. Example: Special weather conditions

Due to its geographical and topographical characteristics, the Brenner corridor is prone to heavy snowfall during winter. Steep gradients and a high proportion of heavy goods vehicles further complicate traffic management under such conditions. This necessitates targeted adaptation strategies to maintain traffic flow and safety.

Existing adaptation measures include:

- Specialised weather forecasts to improve preparedness
- Deployment of snow-clearing vehicles and pre-emptive salting to prevent ice formation
- Traffic restrictions such as overtaking bans or mandatory snow chains, communicated via dynamic signage

These operational responses are not only effective in managing winter conditions but also illustrate the value of the integration of weather forecasting into traffic operations can serve as a transferable adaptation option for other natural hazards, such as heavy rainfall, storms as a trigger for landslides or windthrow.

Limitations and challenges

While operational services are generally well-organised, road user behaviour often poses a significant obstacle. Common issues include neglecting construction signage, inadequate vehicle preparation (e.g. missing winter tyres or snow chains), and disregard for traffic restrictions—particularly among international truck drivers and tourists unfamiliar with local regulations. Such behaviour can undermine well-functioning routines. A typical example is the disruption of snow clearance operations caused by unauthorised overtaking

despite bans (see impact chain). This highlights the need for awareness-raising, targeted communication, and enforcement-oriented adaptations. Education and institutional cooperation can help strengthen coping capacity and improve overall system resilience (Sekhri et al. 2020).



Figure 30 Snow situation along the bottleneck from Brenner Corridor authorities



Figure 31 Operational preparedness from road

Furthermore, forecasting of special weather conditions, like storms or heavy snowfall in the Wipptal region remains challenging due to complex topography and is expected to become even more difficult under changing climate conditions.

Impact Chain, before and after the implementation

The impact chain illustrates a case in which several adaptation options have already been applied. However, the recurring disruption of snow clearance operations due to unauthorised overtaking of lorries - despite existing bans- highlights the ongoing need for awareness-raising through effective communication and enforcement-oriented adaptation. These non-structural measures, such as education, may involve external partnerships for response and recovery or institutional support to strengthen coping capacity, alongside natural capacity (Sekhri et al. 2020).

How does the adaptation solution modify risk reduction?

The operational adaptations do not alter the hazards themselves; their type, frequency, or intensity remain largely unchanged. However, they modify the impact of the hazards by enabling early interventions (e.g., road closures, rerouting). Also, spatial exposure to hazards can be reduced by diverting traffic away from vulnerable areas.

The operational measures do not directly alter the physical assets, but they influence how these assets are used and protected; for example, temporary elements such as mobile barriers or dynamic signage extend the protective asset base during critical periods.

In terms of vulnerability and capacity, this is where operational adaptation has the strongest impact:

- Through awareness raising, communication, and targeted education, particularly for foreign truck drivers or tourists, vulnerability can be significantly reduced.
- The coping capacity increases due to improved information access, preparedness, institutional coordination, and the flexible use of operational systems.

Can they be represented by maps?

The measures can be partially quantified in terms of investments, maintenance, and project lifetime, with some limitations:

- Rough cost estimations are possible for equipment (e.g. snow-clearing vehicles, mobile barriers) and consumables (e.g. salt, fuel).
- Operational adaptation is strongly tied to manpower, which makes cost assessment more difficult. Hourly rates for staff, especially in public-private structures, are often not disclosed.
- Education and awareness campaigns also require investment (e.g. materials, translation, media production), though exact figures vary by campaign scale.

Other measures by which it could be evaluated include improved road safety, reduced accidents, and fewer disruptions; public perception and compliance could also be indicators.

3.4.3 MONITORING AND EARLY WARNING

Monitoring, and early warning systems play a critical role in enhancing adaptive capacity by enabling timely action before, during, or immediately after a hazard event. In mountainous regions, where hazards such as landslides, slope failures, or flash floods can occur with little to no warning, these systems often represent the most viable and cost-effective form of real-time risk reduction.

Unlike structural measures, which can be costly, maintenance-intensive, and location-specific, monitoring technologies offer greater flexibility and scalability. For example, real-time sensors installed along critical infrastructure can trigger automatic road closures once predefined thresholds are reached, thereby reducing human exposure.

The effectiveness of early warning depends on the hazard's failure mechanism. Rapid-onset events may offer limited lead time, while slower-developing hazards with identifiable precursors allow for more reliable alerts and intervention.

This approach represents a form of data-driven adaptation, particularly relevant in the context of climate change, as it allows systems to adjust to evolving hazard patterns and intensities.

Limitations and challenges

Even when individuals are trained and aware of how to respond during a hazard event, losses can still occur, particularly in cases like rockfalls, where physical impact may be unavoidable despite appropriate reaction. Additionally, warning signs may be ineffective if they lack clear, actionable instructions, potentially leading to confusion or inaction. A further limitation lies in human behaviour: people may choose to ignore warnings if no immediate danger is visible, perceiving them as unnecessary or disruptive rather than protective.

How does the adaptation solution modify risk reduction?

Real-time monitoring and early warning will provide the option of rerouting traffic and preventing people from entering a hazardous zone. It lowers the vulnerability and strengthens the coping capacity.

Can they be represented by maps?

As any monitoring and warning measure is directly linked to a geographic locality, these can also be mapped.

3.5 CARIBBEAN CASE STUDY OVERVIEW

The adaptation options proposed for the Caribbean Case Study target the impacts and/or vulnerabilities specific to the disaster scenario, focusing on a major hurricane (Category 5) that would hit one or more of the Eastern Caribbean islands—Dominica, Saint Vincent and the Grenadines, and Grenada — in the present or near future. These mitigation measures do not address the volcanic hazard, as it occurs at a lower frequency. The last event in Saint Vincent occurred in 2001, preceded by events in 1979 and 1902. Dominica has at least nine live volcanoes, of which seven are located within 10 km of the capital, Roseau. However, they have not had significant historical eruptions. The most recent events in the valley of Desolation/Morne Watt were phreatic/steam eruptions (VEI 1 or 2) in 1997 and 1880, and the eruption in Morne Plat Pays/Patates was at least 500 years ago. However, the capital is indicated on the volcanic hazard map as a high hazard zone. Mitigation measures against a volcanic eruption include volcanic hazard monitoring and evacuating people from high- and very high-hazard zones when an eruption is imminent. In Dominica, this involves evacuating the entire North or South part of the island, including the major towns and capital. In Saint Vincent, this includes the entire northern part of the island, which is very sparsely populated (See Figure 32).

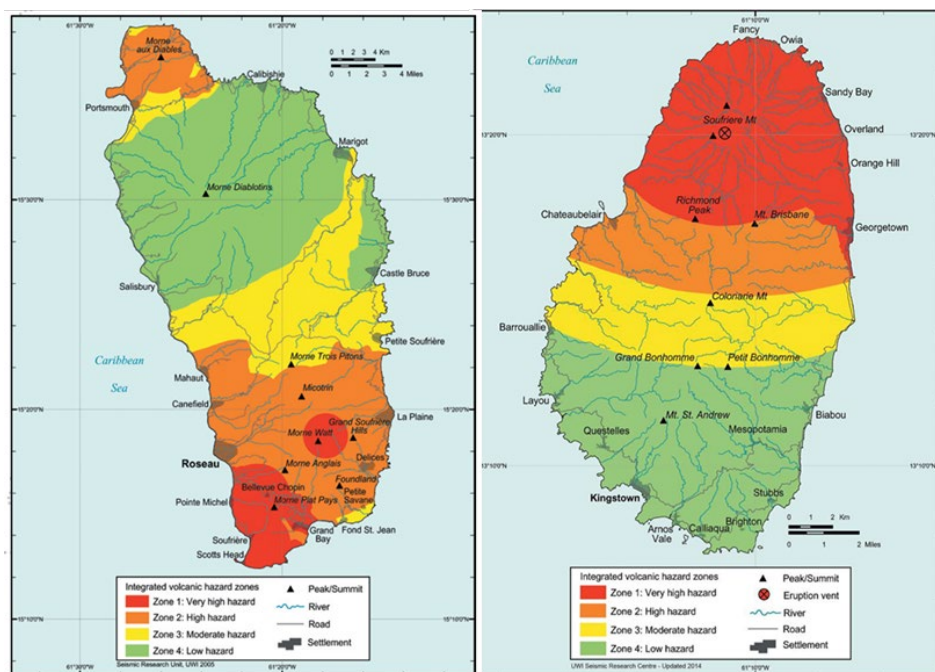


Figure 32 Volcanic hazard maps of Dominica (left) and Saint Vincent (Right). Source: UWI (2012) and NEMO (2022)

Despite the volcanic hazard, the most urgent and frequent concern of the disaster management authorities is Hurricanes. These occur with higher frequency and can be very devastating. This was evidenced by Tropical Storm Erika (2015), Hurricane Maria (2017) and the 2022 trough impact in Dominica. Saint Vincent was hit most recently by Hurricane Beryl (2024, See Figure 33 and 34), Tropical Storm Bret (2023), and Hurricane Elsa (2021 which occurred some months after the Soufriere eruption and intensified the lahars in 2021).

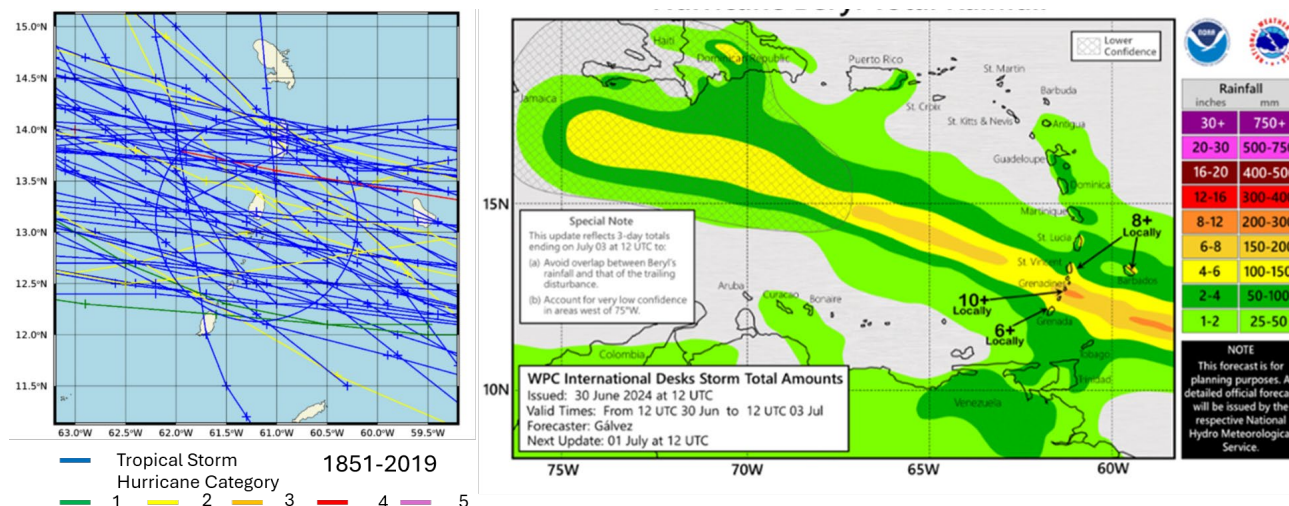


Figure 33 Left: Historical Storms and Hurricanes around Saint Vincent and the Grenadines from 1851-2019 (Source: StormCarib, 2020) . **Right:** Map of Hurricane Beryl Total Rainfall (WMO, 2024)

Methodology

The Impact Chain developed for a hurricane scenario includes many adaptation options that span all phases of the Disaster Risk Management Cycle (i.e., preparedness, response, and recovery). From these, we selected three of the most representative mitigation measures based on their ability to address a broad spectrum of potential impacts and vulnerabilities in the event of a major hurricane, along with associated hazardous events.

This scenario was discussed in workshops in Dominica and Saint Vincent in April 2025. During an earlier workshop in 2024, the impact chains were co-created with the stakeholders, who were from various government departments (Disaster Management Agencies, Red Cross, road department, physical planning, forestry, agriculture, health, etc). In the 2025 workshop, the focus was on mitigation measures, especially those related to preparedness.

The interviews and surveys were based on the following **scenario**:

A major hurricane hitting a Caribbean island, resulting in multi-hazards such as strong winds, and extreme rainfall, which results in other hazards, such as storm surge, flooding, landslides, debris flows, and windfall, leading to damage to buildings, infrastructure, and vegetation

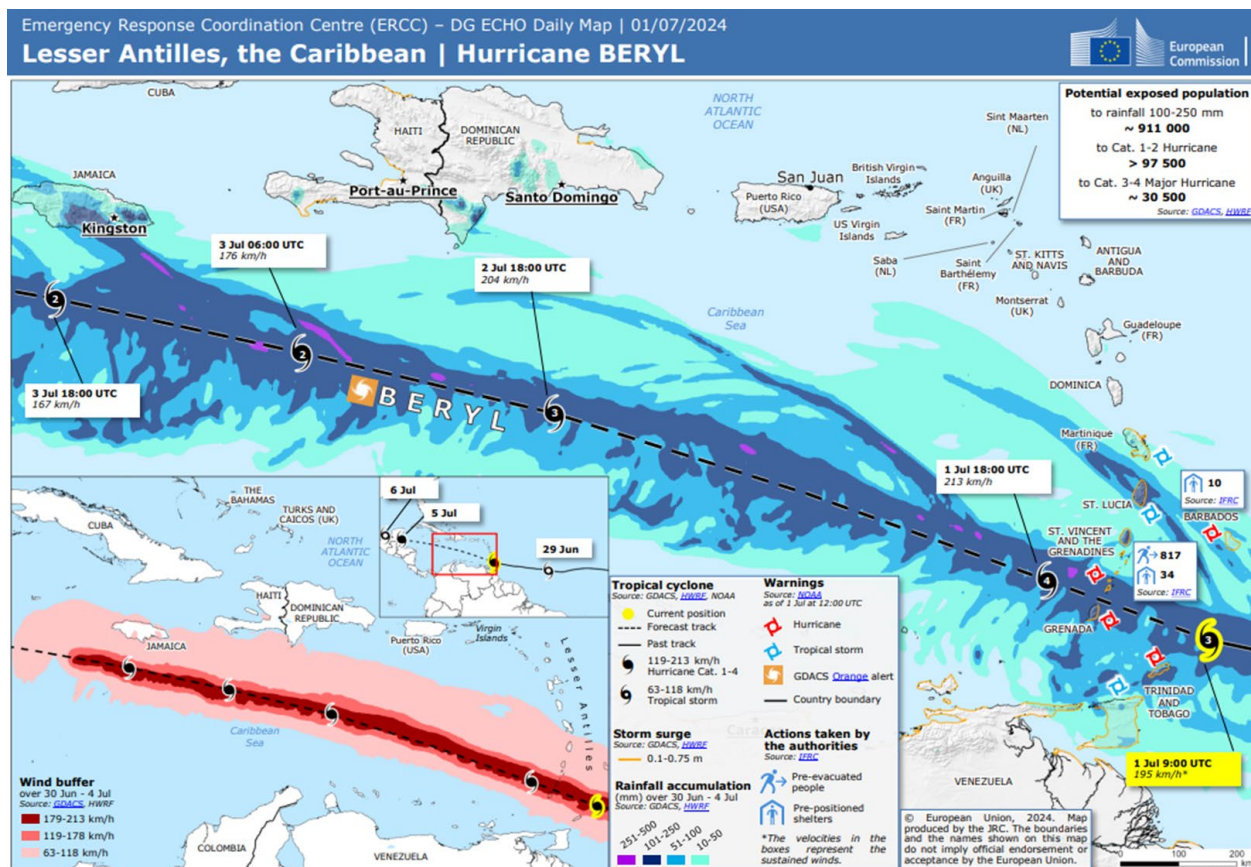


Figure 34: Situation map of Hurricane Beryl on 1 July 2024. Source: Emergency Response Coordination Centre (ERCC, 2024).

Data collected through these qualitative methods was meticulously analysed and structured into primary and secondary hazards, impacts, exposed elements, vulnerabilities and adaptation options. This was complemented by expert knowledge. In the case of vulnerabilities (which convey already existing conditions), adaptation options (which can also be implemented to mitigate the existing vulnerabilities, prior to the manifestation of the hurricane), and certain impacts that involve simulations (e.g., on road disruption and restricted access to intervention areas, human loss, building damage) scientific literature and official reports were also consulted

.Impact Chain, before

The impact chain before the implementation is shown in Figure 35. This impact chain portrays the situation of the historical events from 2021, when the passing of a Hurricane followed a volcanic eruption. The impact chain is quite complicated. For the current scenario, this was simplified in another impact chain version (Figure 36).

In this simplified version, only the most important components are indicated. Heavy rain, strong winds and low pressure accompany the Hurricane. The latter two are responsible for storm surge, which causes coastal erosion and contributes to flooding, in combination with the flash floods caused by the heavy rainfall. The rainfall also triggers landslides, and the windfall contributes many tree logs, which are incorporated into the muddy flows that damage bridges and cause interruptions to the road network. This has numerous indirect impacts, with the disruption of supply chains and the interruption of medical support being among the most

significant. During and after a major Hurricane, harbours and airports may not function for some time, leading to a lack of supplies, fuel, energy and other essential services.

Hurricane

Every year, Saint Vincent faces the risk of storm or hurricane which potentially causing catastrophic damage. Hurricanes and storms are the same weather phenomenon, tropical cyclones, which is generally used by the meteorologists to describe a rotating, organized system of clouds and thunderstorms that originates over tropical or subtropical waters and has closed, low-level circulation. The difference between hurricane and storm is their wind speed. If the cyclone has maximum sustained winds of over 39 miles per hour and below 74 miles per hour, it is categorized as storm. Hurricane is described to have maximum sustained winds of more than 74 miles/hour.

Since 1900, Saint Vincent has been hit by approximately more than 15 hurricanes and named storms. The cyclones are often do not make landfall in Saint Vincent. However, the remnants can also cause gusts of wind, rain, storm surge, and severe damage to the island.

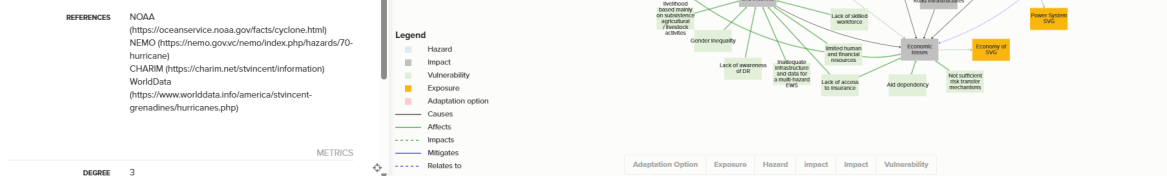


Figure 35: Impact Chain for a hurricane impact on Saint Vincent. Source: <https://kumu.io/Paratus/caribbean-case-study#saint-vincent-multihazard>

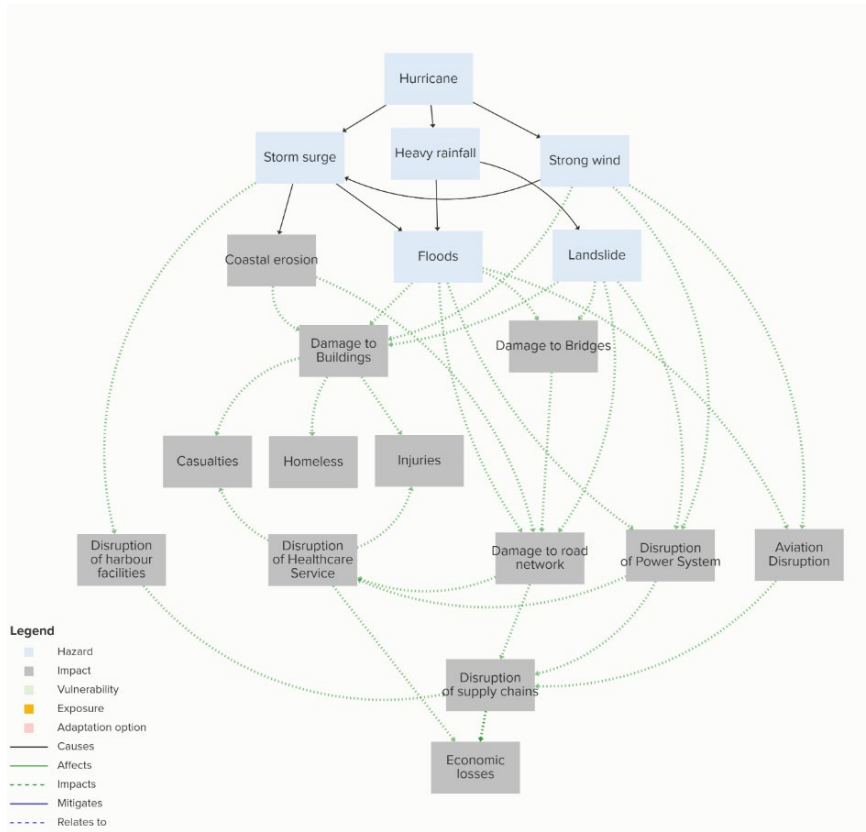


Figure 36 Simplified impact chain of the Hurricane impact scenario

From the large list, which is shown in Annex 4, three adaptation/mitigation measures were worked out in detail.

3.5.1 CONSTRUCTION OF BAILEY BRIDGES & ROAD ASSET MANAGEMENT SYSTEM

Caribbean Small Island Developing States (SIDS), such as Dominica and Saint Vincent, are increasingly affected by the destructive impacts of intensifying hurricanes, flash floods, and landslides. As these events become more frequent and severe, infrastructure systems, especially bridges, face escalating risk. Floodwaters often carry heavy sediment loads, boulders, and tree trunks, leading to catastrophic bridge failure, severed road networks, and the isolation of entire communities.

In this context, Bailey bridges—modular, prefabricated, steel truss bridges—have emerged as a potentially valuable alternative or interim solution to traditional permanent concrete bridges (See Figure 37). We explored the usefulness, limitations, and strategic considerations of employing Bailey bridges in Caribbean nations, focusing on Dominica, and provided a cost-benefit assessment and policy decision framework for their deployment.



Figure 37: Showing the importance of Bailey bridges for maintaining accessibility in mountain Caribbean environments affected by extreme rainfall events. The lower images are of Boetica in Dominica, where a deep ravine was formed during a tropical storm that was crossed by a Bailey bridge.

Bailey bridges were initially developed during World War II as temporary military bridges. Their core features make them particularly suited to emergency and post-disaster scenarios:

- Modular design: Easily assembled without heavy machinery.

- **Portable and reusable:** the components can be transported in standard trucks and reused across multiple sites.
- **Rapid deployment:** they can be constructed within 24–72 hours, restoring connectivity swiftly.
- **Load-bearing capacity:** they are suitable for both pedestrian and vehicular traffic, including emergency vehicles.

Bailey Bridges are useful in flood-prone Caribbean islands for several reasons.

Rapid Post-Disaster Response: In Dominica, bridges are often destroyed during hurricanes and subsequent floods. For example, during Tropical Storm Erika (2015) and Hurricane Maria (2017), over 15 major bridges were either washed away or severely damaged. Bailey bridges enable the rapid reestablishment of access to isolated communities, emergency shelters, and healthcare facilities.

Adaptability to Difficult Terrain: Eastern Caribbean islands such as Saint Vincent and Dominica have a rugged topography, which often complicates the construction of permanent structures. Bailey bridges can be deployed in remote or steep locations where heavy machinery may not be accessible, reducing logistical barriers in mountainous regions.

Sediment and Debris Considerations: Unlike permanent concrete bridges with piers embedded in rivers, Bailey bridges can be installed as single-span structures across narrow rivers or ravines, minimising obstruction to sediment and debris-laden floodwaters. This reduces the risk of structural undermining and debris accumulation, which typically destroy conventional bridge piers.

Cost-Effectiveness in Recurrent Disaster Zones: For communities in high-risk flood zones, investing repeatedly in permanent bridges that are prone to damage may be economically unsustainable. Bailey bridges offer a lower-cost alternative that can serve as either an interim structure while permanent solutions are designed, or a semi-permanent or backup crossing in chronically vulnerable locations.

Despite their benefits, Bailey bridges are not without limitations:

- **Aesthetic and community acceptance:** Some communities may view Bailey bridges as “temporary” or less desirable, leading to lower public support.
- **Maintenance needs:** Steel structures require **regular inspection and maintenance** to prevent corrosion, particularly in humid and saline coastal environments.
- **Load restrictions:** Although structurally sound, they may not be able to support **heavy-duty industrial traffic** or long-term expansion needs.
- **Safety concerns:** Slippery decks and lower side barriers may pose risks without proper surfacing and guardrails.
- **Strategic Decisions:** Where and When to Deploy?

Table 3: Comparing Bailey bridges with permanent bridges

Criteria	Bailey Bridge Preferred	Permanent Bridge Preferred
Risk of repeat flooding	High	Moderate to Low
Terrain accessibility	Remote/Steep	Easily accessible
Urgency	Immediate need	Long-term project
Population size	Small to moderate	High density
Budget constraints	High	Low
Bridge span required	<60 meters	>60 meters
Initial cost per meter	US\$3,000–6,000	US\$10,000–25,000
Construction time	2–5 days	6–18 months

Decision-makers must conduct hazard mapping, cost-benefit analyses, and community consultations to guide these choices, possibly integrating Bailey bridges into a tiered disaster response strategy.

Benefits of Bailey Bridges

- Lower upfront cost.
- Avoidance of economic losses due to delayed recovery (e.g., tourism, agriculture).
- Can be relocated or reused, offering long-term value.
- Intangible Benefits
- Social and psychological reassurance for isolated communities.
- Facilitation of logistics and humanitarian aid delivery during emergencies.

How will the mitigation measure affect the impact chain?

The impact chain is modified as the fast construction of Bailey bridges repairs the damage to bridges and the road network, and makes the road network accessible in a relatively short time, leading to a lower magnitude of cascading impacts. See Figure 38.

Recommendations and Policy Actions

- **Pre-Position Modular Bridge Kits:** Establish strategic stockpiles of Bailey bridge components, particularly in areas prone to hurricanes. Train public works teams and military engineers for rapid deployment.
- **Integrate into National Disaster Plans:** Include Bailey bridges in Disaster Risk Reduction (DRR) and climate resilience strategies. Establish clear guidelines on temporary vs semi-permanent usage.
- **Cost-Sharing Models:** Engage regional bodies (e.g., CDEMA, OECS) and development partners (e.g., World Bank, UNDP) to co-finance bridge kits and training programs.
- **Community Awareness: Educate the public on the safety and purpose of Bailey bridges to ensure community buy-in and maintenance cooperation.**
- **Hybrid Designs:** Explore hybrid solutions, such as Bailey superstructures mounted on elevated, flood-resistant abutments, which extend lifespan and durability.

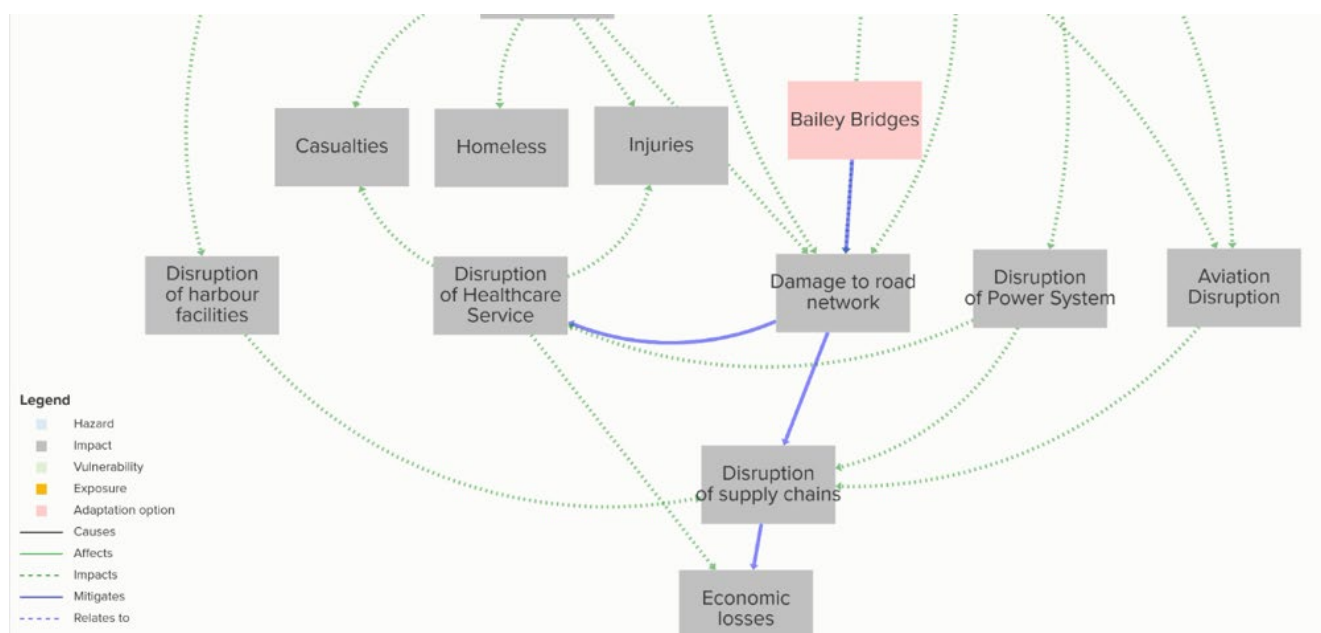


Figure 38: Impact Chain section for Bailey Bridges

Conclusion

Bailey bridges offer a practical, cost-effective, and adaptive solution to the infrastructural challenges posed by hurricanes and floods in Caribbean SIDS like Saint Vincent and Dominica. While not a substitute for all permanent infrastructure, they play a critical complementary role in emergency response, resilience-building, and climate adaptation planning. As extreme weather becomes the new norm, integrating modular bridge systems into national infrastructure strategies will enhance the Caribbean's ability to withstand, recover from, and adapt to climate-driven disruptions.

3.5.2 SHELTER PLANNING

Effective shelter planning is a cornerstone of disaster risk reduction and humanitarian response, particularly in Caribbean Small Island Developing States (SIDS) that are highly vulnerable to extreme weather events such as hurricanes, floods, and earthquakes. This section examines the challenges and considerations associated with emergency shelter planning in these settings. It focuses on issues related to the structural integrity of shelter buildings, their dual use as schools and churches, the vulnerability of shelter populations, and the need for comprehensive inspection, geographic planning, and resource allocation. Examples from Dominica, Saint Lucia, and Grenada illustrate common challenges and evolving practices.

Caribbean SIDS face high exposure to natural hazards due to their geographical location, limited landmass, and clustered settlements. Tropical cyclones and associated flooding frequently displace thousands of people, necessitating well-planned emergency shelter systems. Traditionally, schools, churches, and community centres serve as shelters, but their continued use in this role presents significant structural, social, and logistical challenges, particularly in the aftermath of major disasters when shelter demand is greatest.

Structural Suitability and Functional Conflict

Many designated shelters exhibit structural deficiencies and are not purpose-built for housing displaced populations, lacking essential features such as reinforced roofs, hurricane-resistant windows, and adequate sanitation facilities. Schools and churches often have open floor plans, inadequate ventilation, and limited storage, which pose risks during extended shelter stays. For example, assessments conducted in Dominica

after Hurricane Maria (2017) found that over 60% of shelters used had compromised roofs, non-functional toilets, and no backup power (Government of Dominica, 2018).

Using schools and churches as shelters for extended periods disrupts critical services. Schools may be unavailable for weeks or months, thereby delaying the recovery of education. Churches and temples often lose access to worship and spiritual support, which is essential in the post-disaster context.

Table 4 Typical Duration of Shelter Occupation in Selected Events

Event	Country	Shelter Duration (avg.)	Primary Use Disruption
Hurricane Ivan (2004)	Grenada	3–6 months	Schools closed for 8 weeks
Hurricane Maria (2017)	Dominica	6–12 months	Multiple churches still not reopened in 2019
Hurricane Elsa (2021)	Saint Lucia	2–4 weeks	Minor delays in school reopening

Emergency shelters predominantly serve individuals who are more vulnerable, such as the elderly or chronically ill, women and children, low-income families and persons with disabilities. These populations have specific needs related to accessibility (ramps, toilets, and separate areas), privacy and protection (especially for women and children), as well as dietary and medical support. Unfortunately, many shelters lack the capacity to meet these needs. Overcrowding, limited lighting, and insufficient staffing exacerbate health and protection risks.

The decision which buildings are allocated as shelters must involve a multi-criteria approach, including population density of surrounding areas, proximity to hazard zones (e.g., flood plains, landslide-prone slopes), road accessibility for relief operations and the capacity per capita (square meters per person). Table 5 gives an example of the planning criteria.

Table 5 Shelter Planning Criteria

Criterion	Recommended Benchmark	Notes
Shelter-to-population ratio	1:500–1,000	Adjust for rural vs urban
Minimum floor space	3.5 m ² /person (Sphere Standard)	Excludes communal areas
Sanitation facilities	1 toilet per 20 people	Should include disabled access
Distance to population centre	≤2 km in urban areas	≤5 km in rural areas

Modern shelter planning increasingly uses Geographic Information Systems (GIS) to model optimal shelter locations based on topography, road networks, and population clusters. For instance, Saint Lucia uses GIS to cross-reference hazard zones and shelter locations, improving accessibility and safety metrics. Shelter planning requires software tools, as demonstrated by the tool in Dominica (Figure 39).

During emergencies, fast decisions should be made on the allocation of additional shelters when the number of people requiring shelters is higher than anticipated. This is illustrated in Figure 40 for the situation of Hurricane Beryl in one of the Grenadine islands.

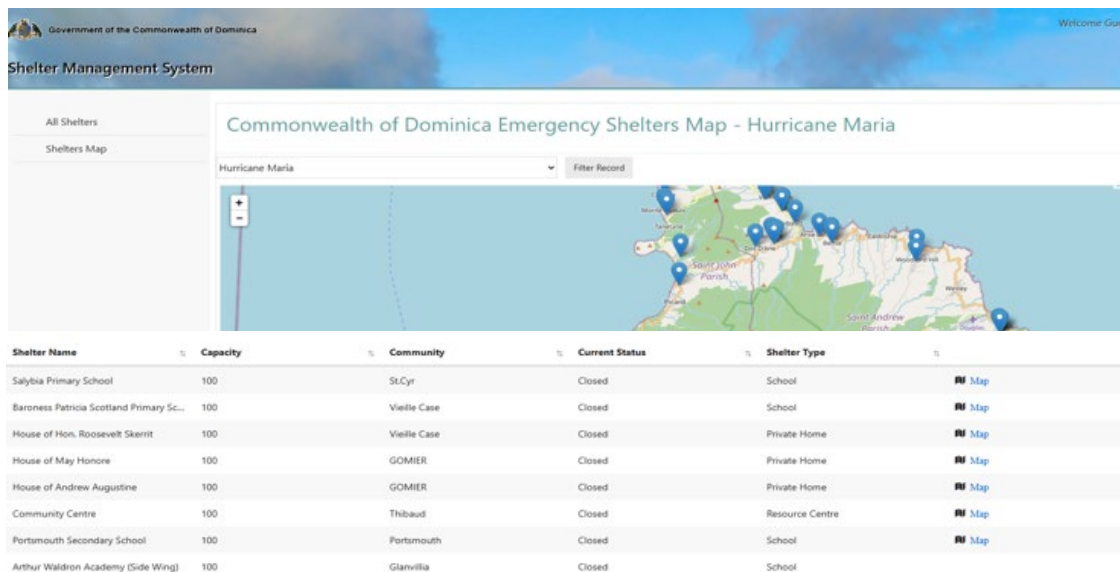


Figure 39: Examples of a shelter management system for the Commonwealth of Dominica (source: ODM, 2024)

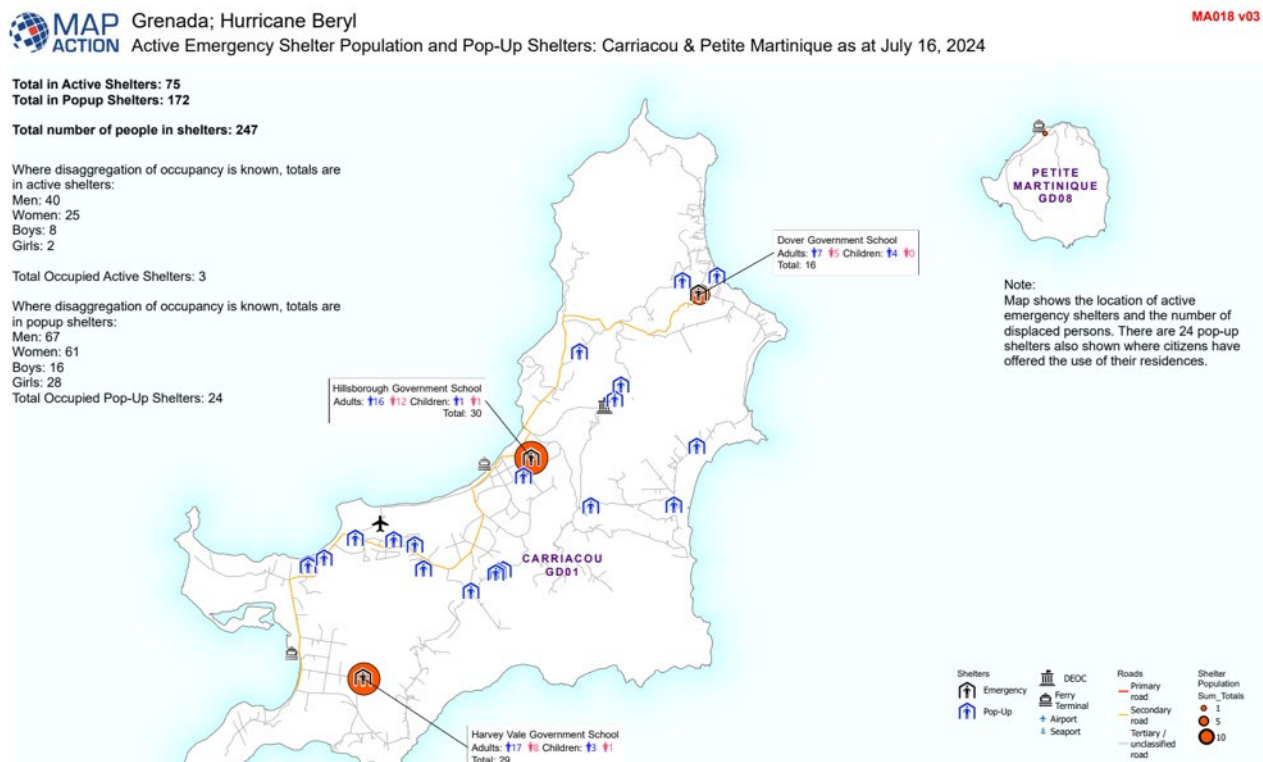


Figure 40: Dynamic pattern of shelters during Hurricane Beryl

How the mitigation measure changes the impact chain

The proper allocation of suitable shelters for housing the most vulnerable part of the population alters the impact chain (Figure 41). Fewer people will be injured, thus resulting in less stress on the medical system. Also, fewer people will be killed, which will result in less serious long-term psychological consequences.

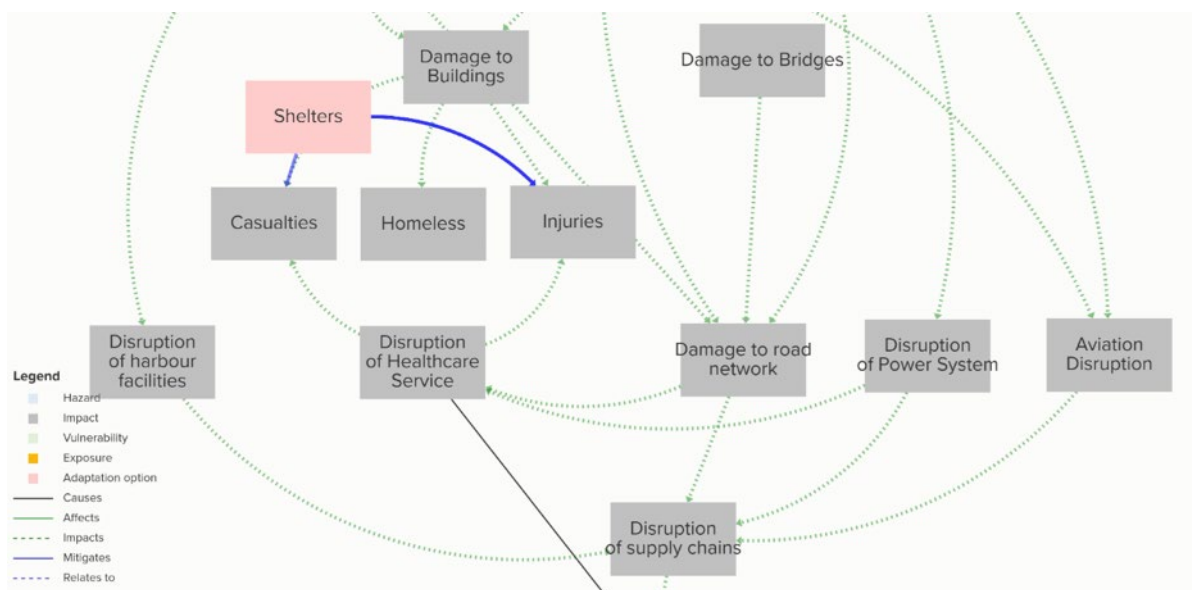


Figure 41: Impact Chain section for Shelters

Routine inspection of shelters is essential to ensure readiness. Many Caribbean nations lack institutionalised shelter inspection regimes, resulting in the degradation of facilities between disasters.

Key elements of shelter inspection:

- Structural integrity assessments (roofing, walls, windows)
- Plumbing and electrical system checks
- Inventory of emergency supplies (mattresses, generators, hygiene kits)
- Fire safety and evacuation signage

Some countries, such as Barbados, have piloted “shelter certification” systems, requiring annual inspections and retrofitting support for buildings designated as shelters.

Policy Recommendations

To enhance shelter planning in Caribbean SIDS, the following measures are recommended:

- Invest in Multi-Purpose Resilient Structures. Governments should prioritise the construction of purpose-built shelters that can serve secondary functions during normal times (e.g., community centres, vocational training spaces) but meet full disaster resilience standards.
- Develop Shelter Inspection and Maintenance Programs. Institutionalise an annual shelter audit conducted by Ministries of Works or Disaster Management Offices, with clear minimum standards for functionality and safety.
- Improve Shelter Accessibility and Inclusion. Ensure all shelters meet universal design standards, with separate areas for vulnerable groups, and facilities for persons with disabilities.
- Use Data and Risk Modelling. Expand the use of GIS and hazard maps to inform the selection and upgrading of shelters. Conduct community consultations to ensure cultural and logistical relevance.

- **Link Shelters to Social Protection Systems.** Integrate shelters with emergency cash transfer and food distribution systems, especially for displaced low-income and elderly populations.

Effective shelter planning in Caribbean SIDS is both a technical and social imperative. The reliance on schools and churches, while pragmatic, exposes structural and operational limitations that compromise disaster response and recovery. By adopting a systems-based approach, involving structural assessment, geographic planning, vulnerability targeting, and data integration, governments can significantly improve shelter safety, inclusivity, and functionality. As climate change intensifies risk, strengthening shelter systems must be a core pillar of national resilience strategies.

3.5.3 CITIZEN BY INVESTMENT PROJECT AND FUNDING FOR RELOCATION OF SETTLEMENTS

One recent example of a severe hurricane impact was Hurricane Maria in Dominica in 2017. The Category 5 storm impacted the Caribbean island with winds of over 250 km/hour, resulting in damage to 90% of the island's housing, and affecting many sectors. The Post-Disaster Needs Assessment (Government of the Commonwealth of Dominica, 2017) concluded that Hurricane Maria resulted in total damages of US\$931 million and losses of US\$382 million, which amounts to 226 per cent of the 2016 gross domestic product (GDP). In the post-disaster phase, several financial measures played an important role in the recovery. One of these was CCRIF and the other one was the Citizenship by Investment Programme.

The **Caribbean Catastrophe Risk Insurance Facility (CCRIF SPC)** plays a crucial role in **climate risk financing** for Caribbean nations by providing **parametric insurance coverage** for natural disasters such as hurricanes, earthquakes, and excess rainfall. Its goal is to enable countries to access **rapid liquidity** following disasters, which is essential for immediate response and early recovery efforts. CCRIF was established in 2007 as the world's first multi-country risk pool. It offers parametric insurance, where payouts are triggered based on modelled losses rather than actual losses. Within 14 days of Hurricane Maria, Dominica received US\$19.3 million from CCRIF under its Tropical Cyclone Policy. This was a parametric payout, triggered based on the modelled wind speed and rainfall associated with Maria's passage over Dominica (CCRIF, 2025). This helped restore critical services, including clearing debris, reopening schools and hospitals, and supporting displaced populations. It reduced the financial impact of natural disasters and helps governments respond swiftly without excessive borrowing or diverting development funds.

Another critical financial instrument in the recovery phase that contributed substantially to the Build Back Better initiative was the **Citizenship by Investment (CBI) Programme** (Figure 42).

Established in 1993, the CBI Programme was designed to attract foreign direct investment by offering Dominican citizenship in exchange for significant economic contributions. Traditionally viewed as a fiscal instrument, the programme quickly transformed into a vehicle for **recovery and climate resilience** after the disaster.

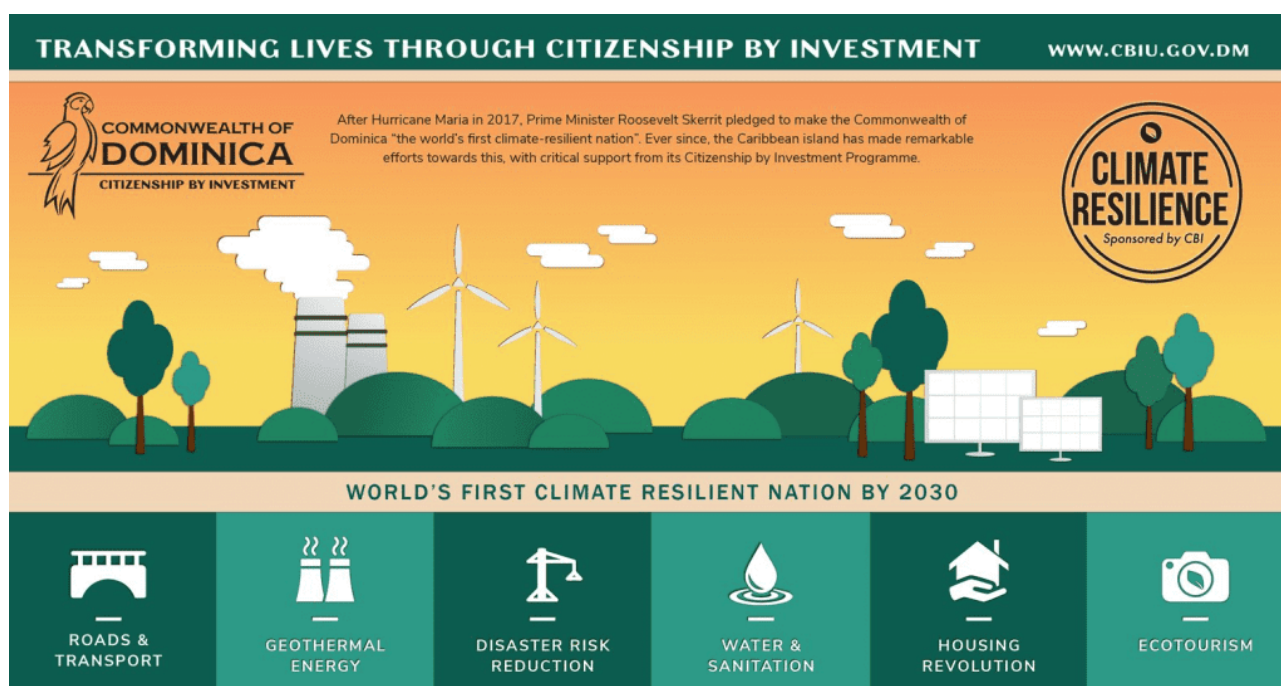


Figure 42 Citizenship by investment infographic. Source: CBBI (2025)

Instead of relying solely on external aid, Dominica channelled millions in CBI funds into recovery in areas like **Bellevue Chopin**, the government constructed entire neighbourhoods of **climate-resilient homes**, equipped to withstand future storms and safely house displaced families from high-risk zones. These weren't temporary shelters; they were long-term, modern homes, with schools, clinics, and access roads (See Figure 43). Bellevue Chopin is one of the resettlement projects in Dominica (See Figure 43 for a map with other examples). Floods and landslides severely damaged the affected settlements, and rebuilding at the exact location was deemed not a viable option. The projects were developed by the Montreal Management Consultants Development Ltd (MMCD, part of Montreal Management Consultants Establishment – MMCE, a UAE/Dubai-headquartered firm active in Dominica since 2015, heavily involved in government infrastructure projects funded through the Citizenship by Investment (CBI) Program (MMCD, 2025). MMCD led reconstruction efforts, including building 2,000+ climate-resilient homes and resettling communities like Petite Savanne after storms – fully financed upfront and later recouped via CBI passport sales. The programme underpinned Dominica's bold national goal to become the **world's first climate-resilient nation**.

The investments extended beyond housing. CBI funds were also used for **renewable energy projects**, notably geothermal development, as well as **smart infrastructure**, and have also been partly used for the construction of the new international airport. MMCD holds the exclusive, no-bid contract with the government to build the new airport (estimated ~ US\$370 M), financed via CBI funds.

However, the Citizenship by Investment Programme has not been without controversy. As international scrutiny of Caribbean CBI programmes has increased, questions have been raised about **transparency**, **due diligence**, and the risks of **economic overdependence** on a single revenue stream. There are also social challenges. Some worry that relocated communities, though safer, may feel **disconnected** from their former livelihoods, especially in agriculture or fishing. It is noted that many of the partly destroyed buildings in the abandoned settlements are occupied by people who tend their nearby fields under poor living conditions.

Despite these hurdles, Dominica's story is one of innovation. By turning citizenship into a tool for resilience, the island has not only rebuilt but redefined what it means to **bounce back better**.

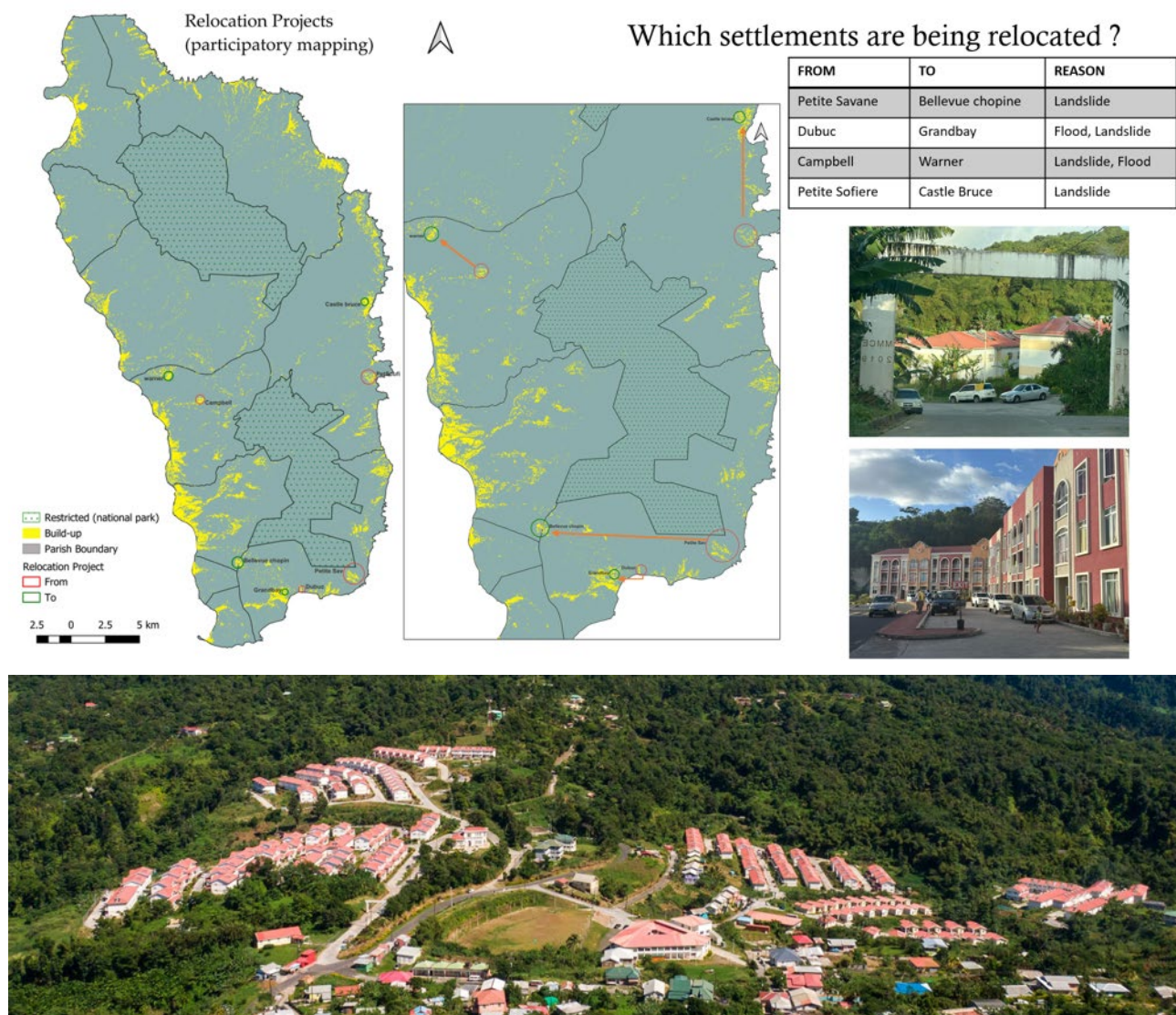


Figure 43: Above: examples of relocation sites funded through the CBI in Dominica (source: Malavika Manoj, MSc thesis). Below: Aerial view of the Bellevu-Chopin relocation settlement (source: <https://mmce.ae/mmcddevelopment/housing/bellevue-chopin/>)

Beyond housing, CBI revenues have financed a suite of national resilience and development projects:

- Energy Sector: Investments in the Dominica Geothermal Development Project, which aims to supply 100% renewable electricity and reduce fossil fuel dependency.
- Expansion of microgrid capacity and energy storage in remote communities.
- Environmental and Climate Programmes: Reforestation and watershed protection in degraded areas. Coastal zone management, including the installation of sea defences and riverbank stabilisation works in flood-prone regions.

- **Health and Education Infrastructure:** Reconstruction and retrofitting of over 12 schools and multiple health facilities to climate-resilient standards. Multi-purpose shelters that double as educational and community centres during emergencies.
- **Tourism and Economic Development:** Government-approved CBI real estate projects such as Secret Bay, Kempinski Hotel, and Tranquillity Beach Resort have generated employment and expanded Dominica's eco-tourism offerings while adhering to sustainable construction guidelines.

Challenges and Policy Concerns

- While the CBI Programme has undeniably supported Dominica's resilience and recovery efforts, it is not without policy risks and challenges:
- **Transparency and Governance:** There is limited publicly available data on expenditure tracking of CBI revenues. Though the Ministry of Finance publishes annual budget statements, more detailed, real-time auditing and disclosure would enhance fiscal accountability.
- **Geopolitical Pressure and Reputational Risk:** International actors, including the European Union, United Kingdom, and United States, have raised concerns about security risks and due diligence in citizenship programmes. These concerns could lead to visa restrictions or diplomatic strain, which would diminish the attractiveness of Dominica's offering.
- **Economic Vulnerability:** An over-reliance on CBI revenues—estimated to account for over 50% of capital expenditure in some years—poses significant macroeconomic risks. Shifts in global investor sentiment, regulatory changes, or external blacklisting could have immediate fiscal repercussions.
- **Social Inclusion and Livelihood Integration:** While physical relocation improves safety, new settlements must be complemented with economic opportunities to ensure long-term viability. Resettled populations often need skills training, access to markets, and transportation networks to maintain or restore livelihoods, especially in agriculture and small enterprises.

How does the mitigation measure affect the impact chain?

The financial instruments, such as the CBI programme and parametric insurance, allow the government to rapidly respond to major events by first restoring major lifelines and critical infrastructure (using CCRIF funds) and then relocating and rebuilding the most impacted settlements in an improved manner. This reduces the building and population losses in the next event (See Figure 44).

Dominica's innovative use of the Citizenship by Investment Programme to finance climate-resilient reconstruction represents a compelling case study in small island developing state (SIDS) adaptation. The CBI Programme has evolved from a fiscal policy tool to a strategic resilience mechanism, enabling the country to finance transformative recovery efforts in the absence of rapid or sufficient international aid.

To sustain this progress, policymakers must ensure that the programme is managed with high standards of transparency, social equity, and fiscal prudence, while remaining responsive to international norms. With

strengthened governance, Dominica’s CBI Programme can continue to serve as a model for climate adaptation finance and disaster risk reduction in the Caribbean and beyond.

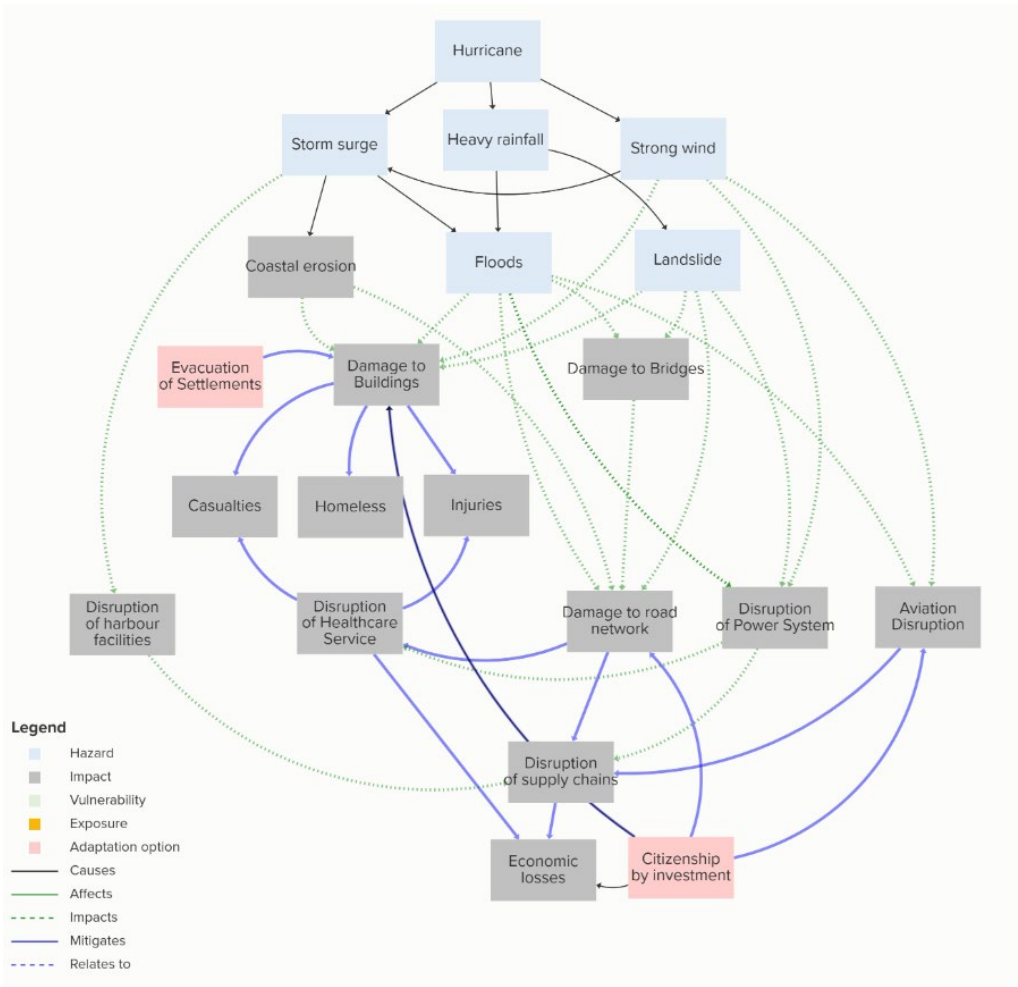


Figure 44 Impact Chain section for Citizenship by Investment

4 CONCLUSIONS

The PARATUS project highlights the critical importance of systemic, anticipatory adaptation strategies to address the growing complexity of multi-hazard risks. By grounding our analysis in detailed impact chains, this report offers a unique lens to visualise and understand the interconnectedness of hazards, vulnerabilities, and impacts. These impact chains not only illuminate cascading risk pathways but also identify strategic points for intervention to reduce risk.

The adaptation options detailed across the four case studies —Bucharest, Istanbul, the Alps, and the Caribbean —demonstrate the tangible value of translating impact chain analysis into practice. From retrofitting buildings in seismic zones and urban regeneration initiatives to operational road management during alpine storms and the deployment of Bailey bridges in hurricane-prone regions, each adaptation measure is rooted in a nuanced understanding of systemic vulnerabilities.

By addressing vulnerabilities before disaster strikes, adaptation strategies contribute not just to reducing physical damage but to enhancing institutional coordination, legal frameworks, early warning capacities, and public resilience. These solutions are not stand-alone fixes, but rather part of a broader resilience-building process that benefits from multi-level stakeholder engagement, local context sensitivity, and cross-sector collaboration.

When mapping the described adaptation options against the 5 categories for disaster resilience goals, it is striking that most of the adaptation options described include a component that speaks to the first goal: to anticipate and improve risk assessment, anticipation and disaster risk management. It highlights the importance to address potential systemic challenges, by recognizing vulnerabilities and planning for effective mitigation measures. While some adaptation options are entirely focused on this disaster resilience goal (e.g. microzonation, engineering protection measures, scenario-based planning) other adaptation options are relating to several of the disaster resilience goals. The linkages to the impact chains depicts how adaptation measures affect the wider local system in each case study specific context.

Ultimately, this report underscores the use of impact chains as an enabler of a structured, transparent, and replicable method for designing locally relevant interventions. The continued integration of such approaches into policy and practice contributes to more robust risk mitigation strategies.

In collaboration with the case study leads, a selection of three adaptation options was then described, linked to excerpts of the impact chains to be included in the Disaster Risk Stakeholder platform (<http://drs-hub.eu>). The RiskChanges tool, part of the DRS hub, will contain a module that compares the benefits of various adaptation options using a Cost-Benefit Analysis, a Cost-Effectiveness Analysis, and a Multi-Criteria Evaluation. This will be part of Deliverables D4.4 and D4.5.

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ANNEX 1 OVERVIEW OF THE ADAPTATION OPTIONS BUCHAREST CASE STUDY

In the Bucharest Case Study 33 adaptation solutions have been analysed under the resilience goals to provide a systemic understanding of the disaster risk management cycle. These are based on the landscape of vulnerabilities and impacts as in the figure below and are organised in a temporal manner to indicate if these vulnerabilities pre-exist the extreme event, if they are occurring during the event (marked in green and grey in the figure below). Some possible solutions and actions that can be taken during response and recovery or are important for strengthening of long-term resilience are marked in red. The three adaptation options described in this section are marked in purple (see figure 43 below).

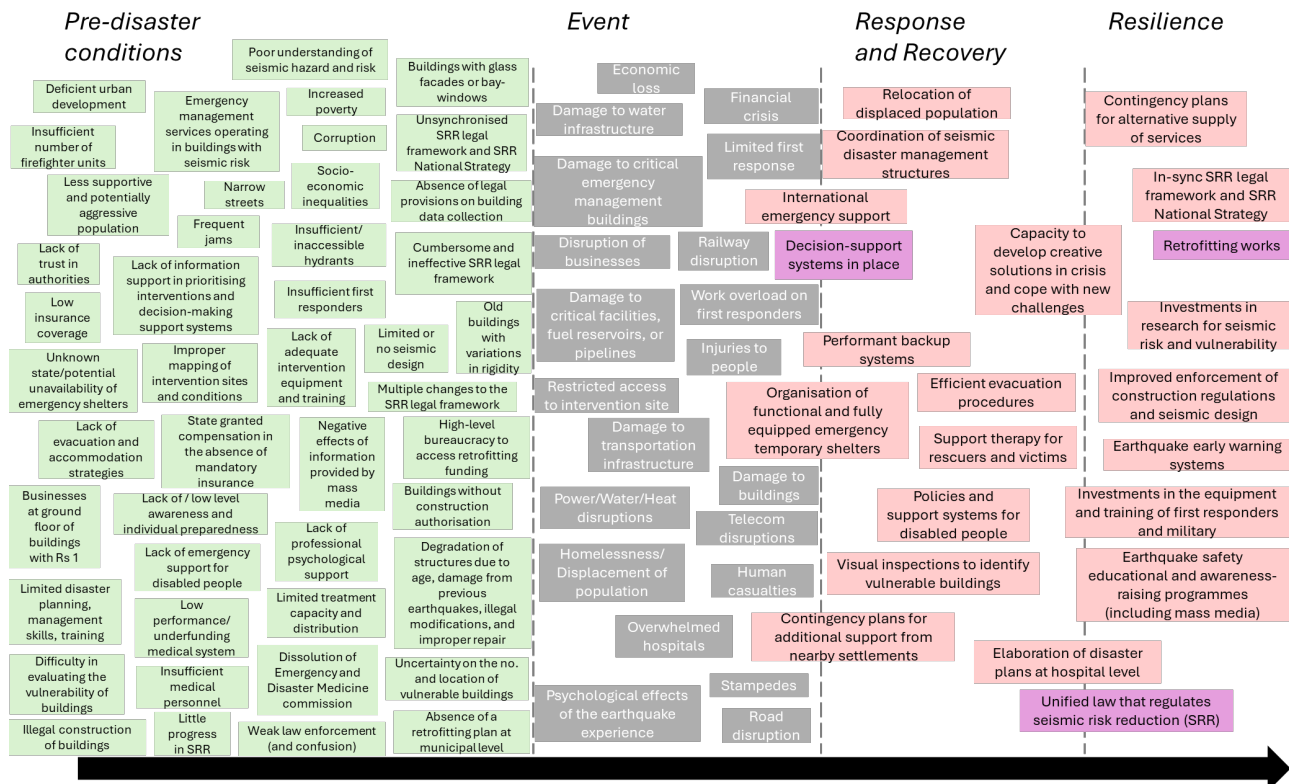


Figure 43 Conceptual landscape of the vulnerabilities and impacts with all identified adaptation options. This follows the timeline developed in the Paratus forensic analysis framework.

Note: these measures do not apply to other disaster scenarios analysed in this case study (e.g., the flood events in 2020-2021 with impacts across Romania, or the multi-hazard seismic-pandemic scenario for Bucharest).

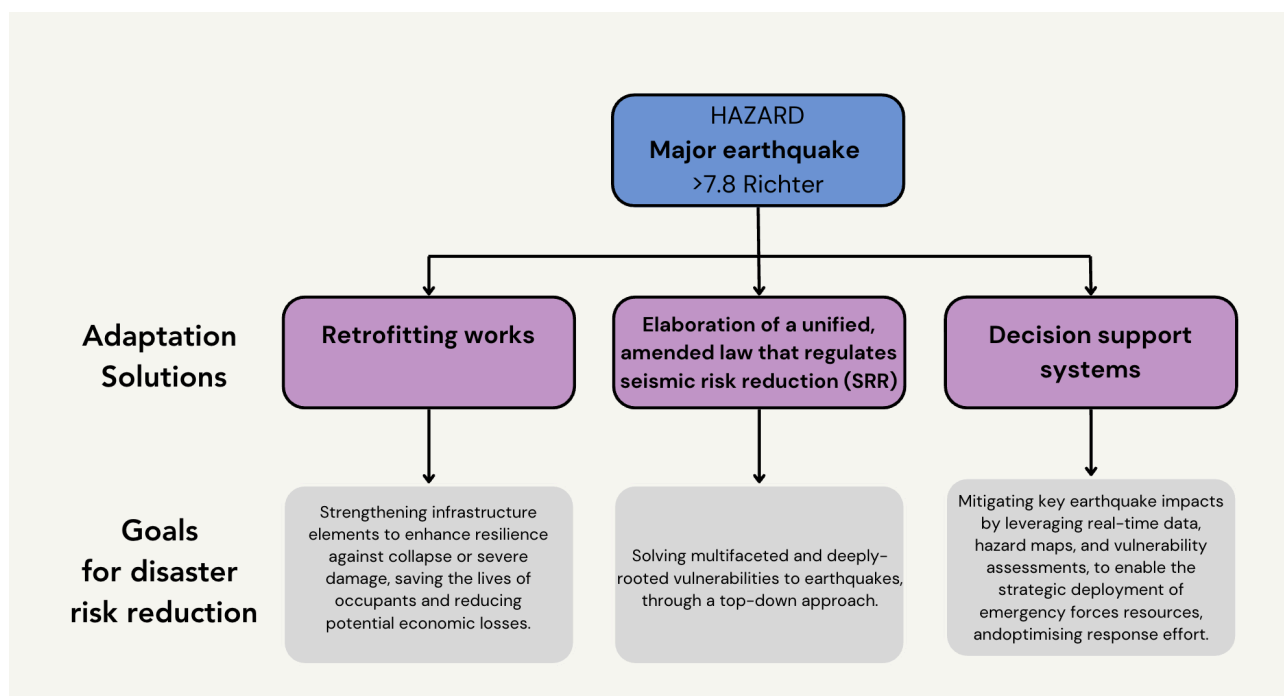


Figure 44 Adaptation solutions and goals for disaster risk reduction in Bucharest for a major earthquake as the hazard.

ANTICIPATE

[Improving risk assessment, anticipation and disaster risk management planning]

These solutions provide the foundational knowledge, regulatory frameworks, technological tools, and institutional structures necessary to understand, assess, and plan for seismic hazards before an event occurs, thereby improving overall risk management.



- Decision-support systems: These systems provide data and analytical tools to help authorities make informed decisions about risk assessment, resource allocation, and planning before and during the response to an earthquake.
- Elaboration of a unified, amended law that regulates seismic risk reduction (SRR)
- Improved enforcement of construction regulations
- Improved enforcement of seismic design
- In-sync SRR legal framework and SRR National Strategy
- Investments in data collection, processing, analysis equipment and staff
- Investments in research regarding seismic risk and vulnerability
- Visual inspections to identify vulnerable buildings
- Financial investment in the medical system



PREPARE

[Increasing risk awareness and preparedness of the population]

These solutions directly empower the population and key institutions with the knowledge, skills, and resources to react effectively to a seismic event, minimising casualties and disruptions through proactive training, planning, and awareness campaigns.

- Changes in the mentality of the public administration
- Earthquake safety educational and awareness-raising programmes
- Education and awareness-raising programmes about the benefits of insurance
- Elaboration of disaster plans at hospital level
- Elaboration of efficient evacuation procedures
- Great capacity to develop creative solutions in crisis and cope with new challenges
- Investments in the equipment and training of first responders and military
- New policies and support systems for disabled people
- Transformation of mass media into an educational factor

ALERT



[Enhancing early warning]

This solution provides the technological means to give prior notice of an impending earthquake, enabling rapid protective actions that can significantly reduce injuries and fatalities.

- Earthquake early warning systems
- Elaboration of efficient evacuation procedures

RESPOND



[Enhancing the Union Civil Protection Mechanism response capacity]

These solutions directly enhance the ability of civil protection mechanisms to act decisively and effectively during and immediately after an earthquake by ensuring coordinated resource deployment, personnel availability, logistical support, and immediate relief for affected populations.

- Contingency plans for additional support from nearby settlements
- Contingency plans for alternative supply
- Hiring of additional personnel
- International emergency support
- Organisation of functional and fully equipped emergency temporary shelters
- Proper coordination of seismic disaster management structures
- Relocation of the displaced population
- Support therapy for rescuers and victims

SECURE



[Ensuring a robust civil protection system]

These solutions collectively create a resilient and adaptive civil protection system by focusing on robust infrastructure (both physical and conceptual), strong legal and institutional frameworks, well-trained personnel, reliable resources, and the capacity for continuous improvement and adaptation, ensuring long-term effectiveness in managing seismic hazards.

- Changes in the mentality of the public administration
- Contingency plans for additional support from nearby settlements
- Relocation to buildings with adequate seismic design

- Reorganisation of hospitals
- Retrofitting works
- Contingency plans for alternative supply
- Decision-support systems
- Elaboration of a unified, amended law that regulates seismic risk reduction (SRR)
- Elaboration of disaster plans at hospital level
- Financial investment in the medical system
- Hiring of additional personnel
- Improved enforcement of construction regulations
- Improved enforcement of seismic design
- Improved institutional coordination of SRR
- Increased funding support for retrofitting from the state/additional sources
- In-sync SRR legal framework and SRR National Strategy
- International emergency support
- Investments in data collection, processing, analysis equipment and staff
- Investments in research regarding seismic risk and vulnerability
- Investments in the equipment and training of first responders and military
- New policies and support systems for disabled people
- Organisation of functional and fully equipped emergency temporary shelters
- Performant backup systems
- Proper coordination of seismic disaster management structures

ANNEX 2 OVERVIEW OF THE ADAPTATION OPTIONS ISTANBUL CASE STUDY

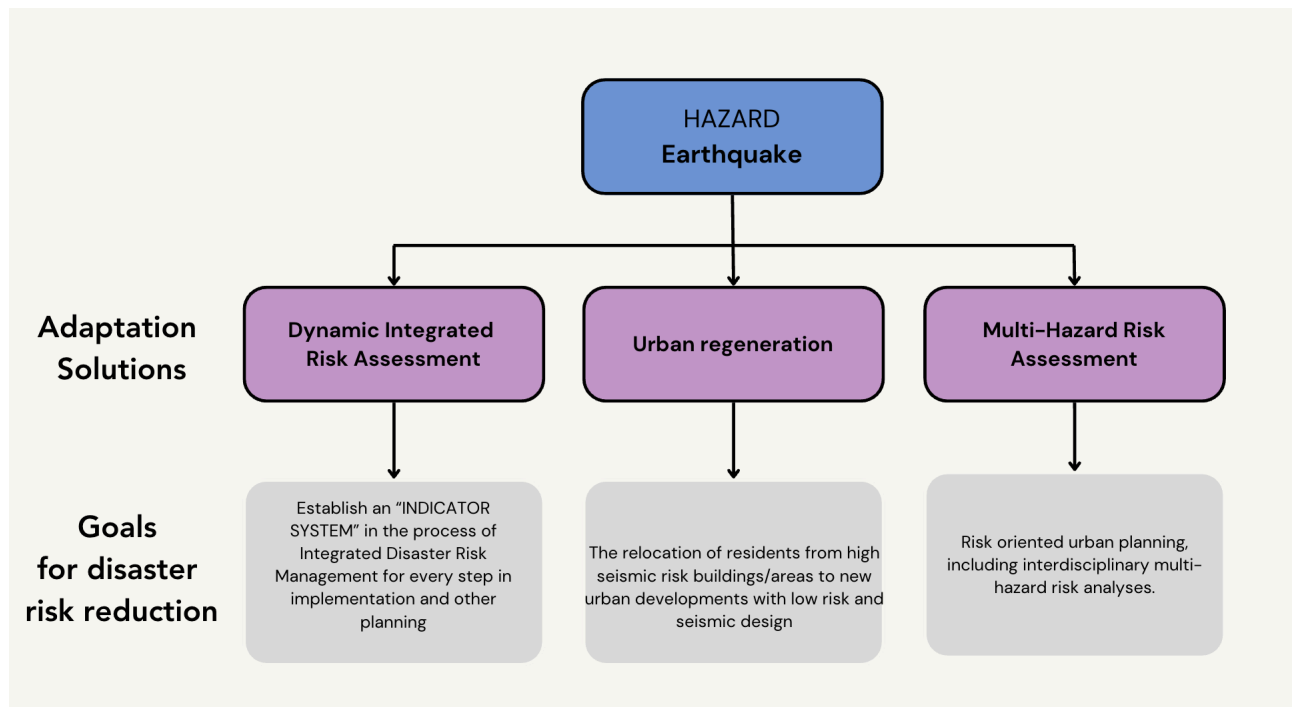


Figure 45 Adaptation solutions and goals for disaster risk reduction in Istanbul for a major earthquake as the hazard.

ANTICIPATE



[Improving risk assessment, anticipation and disaster risk management planning]

- Develop an integrated risk assessment
- Micro zonation
- Urban regeneration
- Increase institutional capacity
- Avoid gaps in regulations
- Enhance infrastructural capacity
- Encourage public-private partnership in housing production
- Prevention and precautionary measures for triggered landslides and flood-prone areas
- Retrofitting public buildings (especially health facilities)
- Rebuilt or retrofit buildings
- Digital twinning of the city

PREPARE



[Increasing risk awareness and preparedness of the population]

- Encourage public-private partnership in community awareness
- Enhance coordination and collaboration among institutions, NGO's and community
- Integrate disaster awareness programs at schools
- Develop public awareness programs for different groups in society
- Emergency plans for hazardous industries

- Encourage volunteering

ALERT



[Enhancing early warning]

- Early warning system to shut down the infrastructure system (i.e. natural gas)
- Install early warning system for hazardous industrial facilities

RESPOND



[Enhancing the Union Civil Protection Mechanism response capacity]

- Develop strategic and tactical approaches for disaster logistics
- Ensure storage capacity and location of goods for emergency
- Provide temporary shelters compatible with different weather conditions
- Social support for disadvantaged population
- Psychological support

SECURE



[Ensuring a robust civil protection system]

- Ensure evacuation routes and areas
- Security plans for the aftermath of a disaster
- Secure infrastructural systems (especially potable water resources)

ANNEX 3 OVERVIEW OF THE ADAPTATION OPTIONS ALPS CASE STUDY

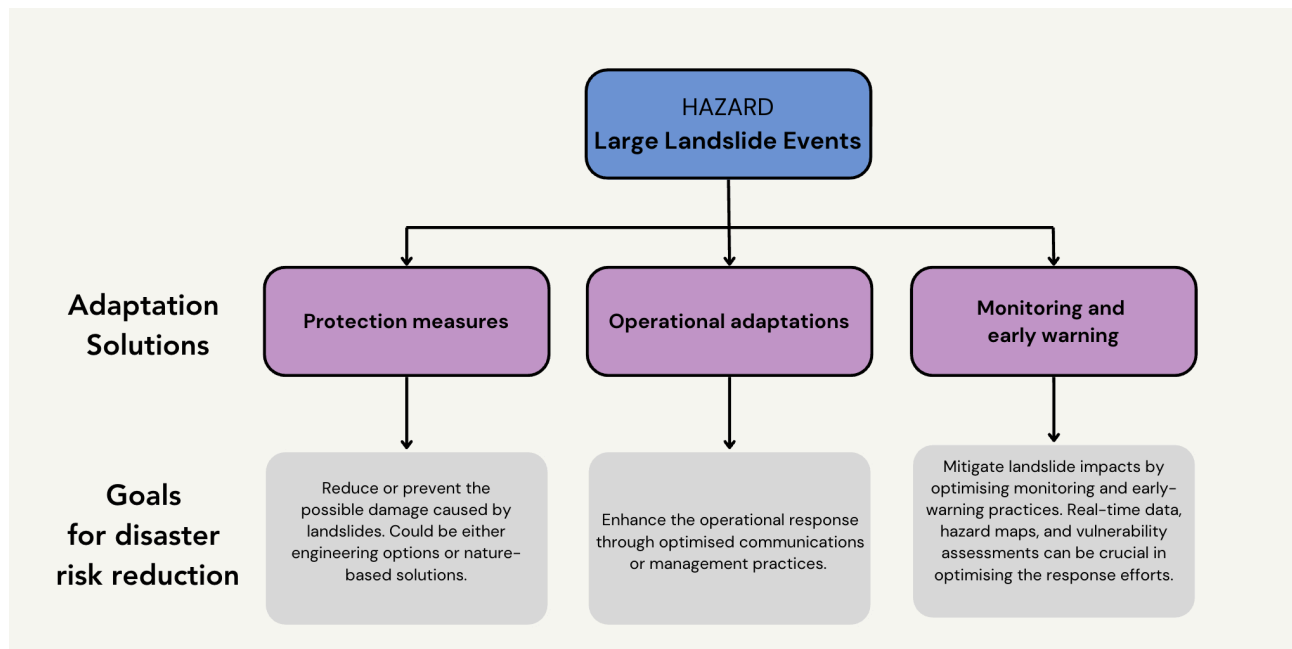


Figure 46 Adaptation solutions and goals for disaster risk reduction in the Alps for a large landslide event as the hazard.



ANTICIPATE

[Improving risk assessment, anticipation and disaster risk management planning]

- Strengthen education on climate change and its impact on disaster risks.
- Enhance training in disaster risk management and emergency response.
- Develop decision-support systems with integrated data and analytical tools for planning and response.
- Facilitate timely and accessible data sharing across relevant institutions.
- Invest in data infrastructure, equipment, and skilled personnel.
- Support targeted research on landslide risk, exposure, and vulnerability.
- Conduct regular visual inspections and geotechnical surveys in hazard-prone areas.
- Ensure sustained funding for education and research institutions in hazard-related fields.
- Expand investment in real-time monitoring and early-warning systems



PREPARE

[Increasing risk awareness and preparedness of the population]

- Shift in public administration culture toward proactive risk governance.
- Promote risk-aware attitudes and behaviours within the general public.
- Implement disaster education and awareness programmes.
- Raise awareness on the value of insurance for disaster recovery.
- Develop emergency response plans for civil protection and healthcare services.
- Establish clear and efficient emergency protocols for critical infrastructure.

- Invest in training and equipping first responders and civil protection teams.
- Engage mass media as a tool for risk education and public outreach.

ALERT



[Enhancing early warning]

- Enhance landslide early warning systems
- Invest in large-scale risk assessments
- Elaboration of efficient emergency procedures
- Enhance mobile signs along roads for early information about events

RESPOND



[Enhancing the Union Civil Protection Mechanism response capacity]

- Contingency plans for additional support from nearby towns and centres
- Hiring of additional personnel
- Organisation of functional and fully equipped emergency water and grocery providers in case of a long-term interruption
- Proper coordination of landslide disaster management structures, also across borders, with similar guidelines

SECURE



[Ensuring a robust civil protection system]

- Foster a proactive risk culture in public administration and society.
- Enhance long-term education in risk and resilience.
- Increase investment in continuous monitoring and early warning systems.
- Develop contingency plans leveraging support from similarly affected regions.
- Implement decision-support systems for informed planning and response.
- Establish a unified legal framework for cross-border, multi-hazard risk governance.
- Ensure sustained funding for risk-related education and training.
- Improve stakeholder engagement and governance mechanisms.
- Expand state and external funding for civil protection.
- Invest in data infrastructure, including personnel, equipment, and analysis tools.
- Support research on landslide risk, exposure, and vulnerability.
- Strengthen training and equipment for first responders and civil protection units.
- Ensure effective coordination across hazard assessment institutions

ANNEX 4 OVERVIEW OF THE ADAPTATION OPTIONS CARIBBEAN CASE STUDY

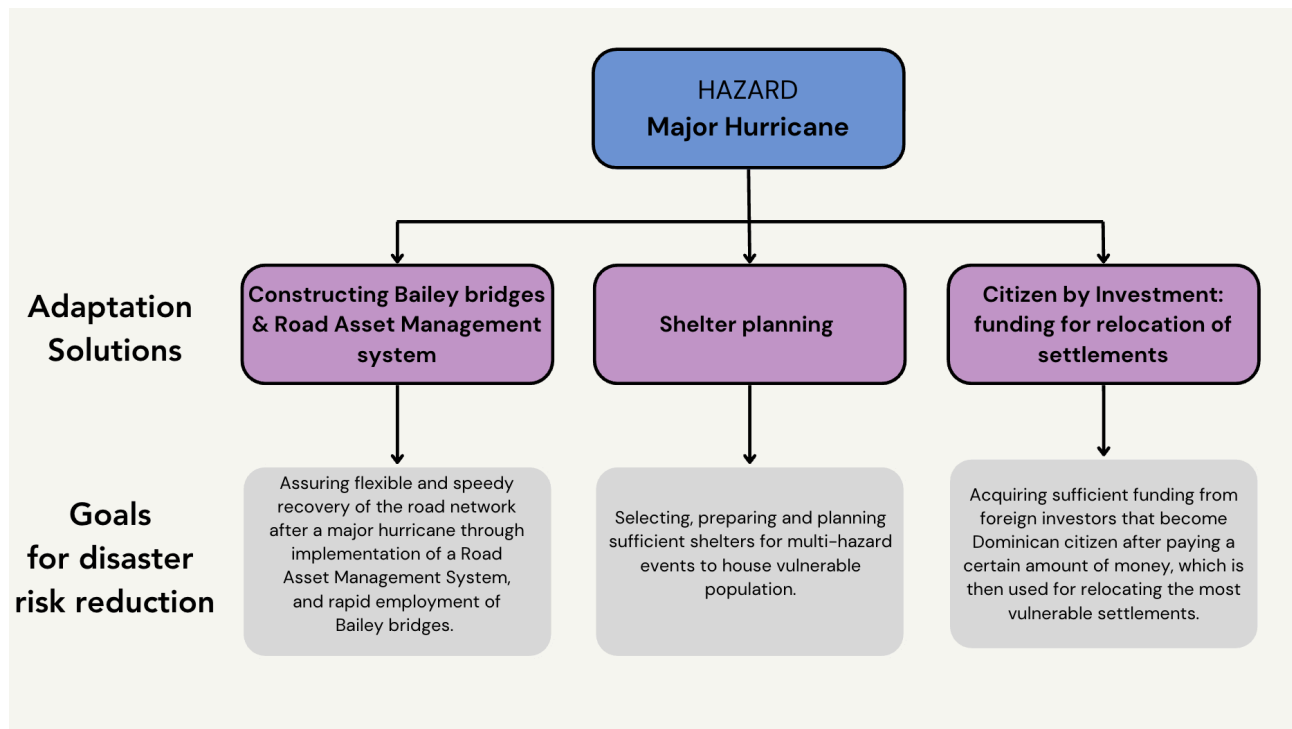


Figure 47 Adaptation solutions and goals for disaster risk reduction in the Caribbean for a major hurricane as the hazard.



ANTICIPATE

[Improving risk assessment, anticipation and disaster risk management planning]

- **National Emergency Management Organisation (NEMO):** Central coordinating body for disaster risk management, responsible for preparedness, response, and mitigation strategies.
- **National Emergency Plans:** Development and periodic revision of multi-hazard contingency and response plans.
- **Community Disaster Committees:** Local groups trained and supported by NEMO to enhance community-level preparedness and response.
- **Partnerships with Agencies:** Collaboration with regional organisations like the Caribbean Disaster Emergency Management Agency (CDEMA) and international bodies like the UN and the World Bank.
- **Local plans and regulations:** Local land use or comprehensive plans embody the goals, values and aspirations of the community, as expressed through a process of community engagement. The plan should identify current development patterns and trends as well as areas where future development should and should not occur. The plan should include policies and ordinances that steer development away from hazard-prone areas, such as floodplains, to avoid putting people and property at risk. In some cases, local plans can work at cross purposes. For example, a capital improvement plan may call for extending water and sewer lines to an area that is vulnerable to

natural hazards. Emergency managers, planners and others in a community should coordinate in preparing plans to ensure consistency across plans; that is, consistent goals, policies, and strategies.

- **Structure and Infrastructure projects:** these actions involve modifying existing structures and infrastructure to protect them from a hazard or remove them from a hazard area. This could apply to public or private structures as well as critical facilities and infrastructure. This type of action also involves projects to construct manmade structures to reduce the impact of hazards.
- **Natural Systems Protection.** These are actions that minimise damage and losses and also preserve or restore the functions of natural systems. Examples include: Sediment and erosion control, Stream corridor restoration, Forest management, Conservation easements, Wetland restoration and preservation
- **Decision-support systems:** these systems provide data and analytical tools to help authorities make informed decisions about risk assessment, resource allocation, and planning before and during the response to a hurricane or other events.
- **Road Asset Management System:** where the items of the transportation network are recorded, where the damage is recorded and where the most sensitive components are evaluated.
- **Having several Bailey bridges** available that can be used rapidly after a major event to restore traffic in crucial parts of the road network.
- **Citizen by Investment initiative,** where upon investing in real estate or infrastructure, a Minimum donation of USD 200,000
- **Building guidelines for wind resistant buildings;** Guidelines for water harvesting of rainwater and storage in cellars in dry areas without surface water;
- Dominica has a **policy** to become the first **climate-resilient island country** in the world.
- **Hazard maps:** Updated volcanic, flood, and landslide hazard maps inform planning and evacuation zones.
- **Improved risk assessment:** for different sectors and different purposes.
- **Zoning Regulations:** Efforts to discourage or restrict construction in high-risk areas.
- **Investments in data collection,** processing, analysis equipment and staff
- **Visual inspections** to identify vulnerable buildings, especially focusing on schools
- **Financial investment** in the education, social and medical system



PREPARE

[Increasing risk awareness and preparedness of the population]

- **Hazard Monitoring:** Installation of seismic monitoring equipment, particularly for the La Soufrière volcano (Saint Vincent), and maintaining a network of meteorological and hydrological stations.
- **Real-Time Information Dissemination:** Use of radio, social media, SMS alerts, and community networks to share early warnings
- **Online news media:** that cover the relevant aspects related to preparedness.
- **Shelter planning:** identification of buildings that may serve as shelters, inspection and monitoring, allocation planning;

- Developing procedures for **notifying citizens of available shelter locations** during and following an event
- **Community-based disaster management projects:** focusing on self-sufficiency in times of disaster impact
- **Distribution of emergency resources** through logistic hubs around the Caribbean and within individual countries
- **Educational and awareness programs:** These are actions to inform and educate citizens, elected officials, and property owners about hazards and potential ways to mitigate them. These actions may also include participation in national programs, and although this type of mitigation reduces risk less directly than structural projects or regulation, it is an important foundation. A greater understanding and awareness of hazards and risk among local officials, stakeholders, and the public is more likely to lead to direct actions. Examples include: Radio or television spots, Websites with maps and information, Real estate disclosure, Presentations to school groups or neighbourhood organizations
- **Creating mutual aid agreements** with neighbouring communities to meet emergency response needs.
- **Purchasing radio communications equipment** for the Fire Department.
- **Distribute road cleaning equipment** near the most sensitive locations along the road network to restore function soon after an event
- **Cleaning of drainage channels and removing vegetation and sediments.**
- Multi-hazard safety educational and awareness-raising programmes
- Education and awareness-raising programmes about the benefits of insurance
- Elaboration of **disaster plans at the hospital level**
- Elaboration of **efficient evacuation procedures**
- Create capacity to develop creative solutions in crisis and cope with new challenges
- **Investments in the equipment and training** of first responders
- New policies and support systems for **disabled people**

ALERT



[Enhancing early warning]

- Volcanic Early Warning
- Development of a **Multi-Hazard Early Warning System**
- Development of **Early Action Protocols** and **Impact Based Forecasting**
- **Stocking of relief items**
- Trim or cut all overhanging trees and branches.
- Clean or clear all drains around houses.
- Ensure that **roofs are securely fastened.**
- Ensure that people have **emergency supplies and fuel.**
- **Evacuate vulnerable people** to shelters.
- **Evacuating livestock**

- Have extra **clean containers available to store water**.
- Ensure that **people have water and food** to last for three days or longer.
- Make **arrangements to shelter with friends and family**.
- Ensure that **people have a plan** for their family in the event of an emergency.
- Fishermen and small craft operators should prepare a plan to secure boats and Fishing gears.
- Activation of Volunteers

RESPOND



[Enhancing the Union Civil Protection Mechanism response capacity]

- Set-up **crisis coordination team**, and local connections
- **Reestablish communication** via mobile network
- Use of Bailey bridges to **restore road connections**;
- **Cleaning of roads** covered by vegetation and debris.
- **Activate volunteers**
- **Repairing powerlines**
- **Damage assessment** using satellite data, using COPERNICUS, ERCC and other agencies
- Relocation of most threatened settlements;
- Efficient emergency and relief programs.
- Restoration of infrastructure and vital life support systems happens in this phase.
- The community identifies local resources to form a long-term recovery group (LTRG), and the initiation of plans for permanent housing begins.