Rapid Multi-Risk Needs Evaluation and Planning Platform

101193586 - EMERGE - UCPM-2024-KAPP-PV

CBR Exposure, Resources and Capacity Portfolio

Socio-Economic Vulnerability Assessment

Work package:	3
Deliverable Number:	3.1
Lead Beneficiary:	UPT-FCE
Coordinator:	IZIIS
Contributing Beneficiaries:	AUTH, IUSS, IZIIS, EUCENTRE, CMC, PRD, AKMC, INFRATECH
Dissemination Level:	Public
Version:	1.0
Due Date:	October 31, 2025
Submission Date:	November 14, 2025

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WP3 CBR Exposure, Resources and Capacity Portfolio

D3.1 Socio-Economic Vulnerability Assessment

WP-03 | D.3.1

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November 14, 2025

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Executive summary

Deliverable D3.1 presents the development of the Population–Socio-Economic Vulnerability Database and the corresponding Socio-Economic Vulnerability Assessment for the cross-border region (CBR) shared by Albania, Greece, and North Macedonia. The objective is to establish a harmonised, comparable dataset describing the socio-demographic and economic conditions of each municipality and to quantify their relative social vulnerability.

The assessment follows the Social Vulnerability Index (SoVI) framework by Cutter et al. (2003) and integrates 35 indicators grouped into seven thematic dimensions: Population, Education, Economy, Health, Infrastructure, Habitat, and Governance & Institutional Capacity. These indicators capture the demographic structure, socio-economic conditions, institutional performance, and service availability that influence a community's ability to prepare for, cope with, and recover from hazardous events.

To address differences in heterogeneous data availability and indicator relevance, two scenarios were developed:

- Scenario S1 uses a common "importance" weighting across the entire cross-border area but assigns country-specific "quality" weights, acknowledging that data are not uniformly available at the municipal level (e.g., some variables exist only at prefecture, regional, or national scale).
- Scenario S2 applies country-specific weights for both "importance" and "quality", reflecting expert judgment on the relevance of each indicator within its thematic group and the reliability/resolution of the corresponding data source.

The results show that Albania presents the highest overall level of social vulnerability, while North Macedonia displays the greatest sensitivity to the weighting approach. The shift to country-specific weights (S2) produces the most significant changes in the internal ranking of North Macedonian municipalities.

Health emerges as the most critical and uniformly high-vulnerability dimension across the entire cross-border region. At the same time, the ranking of the countries in terms of social vulnerability changes depending on the thematic group considered: Greece scores highest in Population and Governance, North Macedonia in Economy, while Albania shows the highest vulnerability in the remaining groups such as Infrastructure, Habitat, and Education.

The resulting database, index values, and maps, provide an essential evidence base for civil protection authorities, local governments, and EMERGE stakeholders. They support the identification of priority municipalities, the planning of targeted interventions, and the enhancement of cross-border cooperation for disaster preparedness and emergency response.

1. Introduction

The risk posed to a population by natural and human-induced hazards encompasses not only the nature of the hazard and the degree of physical vulnerability, but also the capacity of the affected society to effectively manage and respond to the consequences of a disastrous event. These social effects are largely ignored in natural hazard and human-induced risk assessment, mainly because of the difficulty quantifying the human dimensions within a hazard zone. Recent natural-hazard events, like the Haiti earthquake of 2010, the 2010 floods in Pakistan or the 2023 earthquake in Turkey, provided overwhelming reminders of the susceptibility of communities to devastating loss of lives, livelihoods, and property from natural hazards. People react differently in an event's aftermath, adjust to its circumstances in dissimilar ways, and recover differentially. While there is a myriad of approaches to understand extreme impacts, including the delineation of vulnerability, resilience, and risk, it is the dynamic interrelationships between these that are quickly becoming the focal point for politicians, emergency managers, planners, stakeholders, and the general public (Cutter et al., 2003).

With the goals of the EMERGE project in mind, it is of paramount importance to carry out a social vulnerability assessment to evaluate the potential impacts that similar levels of hazards might have on different communities, within the same country/region or between different countries, around their borders. Such impacts depend on the condition of each community's social fabric, which includes pre-existing socioeconomic characteristics related to the capacity of groups to prepare for, respond to, and recover from damaging events (Burton and Silva, 2016). Social vulnerability indicators are thus crucial because they help to identify and support the populations most at risk during disasters, ensuring no one is left behind, while, according to equity principles, resources and aid are distributed fairly, addressing systemic inequalities that worsen the impact on marginalised groups.

There are several available approaches to quantity socioeconomic vulnerability. Cutter et al. (2003) have proposed a methodology based on the definition and construction of a composite index called *SoVI*. It examines certain available census indicators (variables) through factor analysis to score the vulnerability of a region with respect to other regions within the area of study. In other words, *SoVI* is an indicator-based approach that quantifies the social vulnerability of a community and subsequently aids decision-makers in assessing the resilience level of that community, when affected by external stresses, such as natural or human-induced hazards, on human health and activities (Nafeh et al., 2020). Its earliest use concerns the quantification of community-level susceptibility to environmental hazards in the United States (Cutter et al., 2003). The approach quickly became a reference point for hazard mitigation, emergency management, and climate adaptation planning (Cutter et al., 2003). It is worth noting that index-design choices-variable selection, normalisation, and factor retention embedded with the approach can materially affect spatial rankings, an important caveat when such indices inform high-stakes risk-reduction or funding decisions (Schmidtlein et al., 2008; Tate, 2012).

Considering that, in some cases, certain indicators are not publicly accessible, thus rendering the quantification of a vulnerability score at least difficult, Burton et al. (2017) proposed the Resilience Performance Scorecard (RPS). It seeks to enhance the effectiveness of the *SoVI* framework by employing specifically designed questionnaires to obtain targeted information. The methodology provides a multi-scale self-evaluation tool that can apprehend the fundamental practical and policy-making fields for urban resilience enhancement through qualitatively derived information. When addressed properly and effectively, social vulnerability decreases which reciprocates in reducing human distress and reduces expenditure for public assistance and services to be allocated after the occurrence of an event.

In line with the methodology outlined by Cutter et al. (2003), Carreño et al. (2007) developed the Risk Management Index (RMI), which consolidates a set of indicators to evaluate risk management performance and effectiveness. These indicators reflect organisational structure, developmental progress, institutional capacity, and actions implemented to reduce vulnerability and potential losses, facilitating crisis preparedness, and enabling efficient disaster recovery within a specific area. The RMI is intended to provide a comprehensive assessment of risk management initiatives. It offers a quantitative measurement based on established qualitative targets or benchmarks that risk management programmes should strive to attain. The RMI's design encompasses establishing achievement scales or determining the gap between current conditions and objective thresholds, or comparative standards found in reference countries, sub-national regions, or cities. It is constructed by quantifying four public policies, each of which is described by six indicators. These policies encompass risk identification, risk reduction, disaster management, as well as governance and financial protection. Risk identification involves individual perception, social representation, and objective assessment. Risk reduction focuses on prevention and mitigation strategies. Disaster management includes both response and recovery processes.

More recently, the Megacity Indicator System for Disaster Risk Management (MegaIST) was proposed by Mentese et al. (2016). It is an integrated framework designed to assess earthquake risk in Istanbul by combining physical, social, and institutional dimensions. The methodology follows a holistic, multi-criteria approach inspired by the IDB–IDEA Indicators Program (Cardona et al., 2005), and it is structured around three complementary indices: the Urban Seismic Risk Index (USRi), the Coping Capacity Index (CCi), and the Disaster Risk Management Index (DRMi). USRi quantifies earthquake risk by integrating physical risk (expected casualties, building and infrastructure damage, road blockages, and fire outbreak probabilities) with social fragility and lack of resilience. CCi measures the municipality's operational ability to respond to and recover from disasters. This includes resource availability for debris removal, rescue and relief operations, lifeline restoration (gas, water, sewage), and shelter site support. Capacity is expressed as a ratio between the supply and demand of operational resources derived from scenario-based risk assessment. Finally, DRMi provides qualitative performance indicators to evaluate institutional and policy-level disaster management capabilities across four domains: legal and institutional frameworks, risk reduction implementation, response and recovery readiness, and strategy and coordination.

Among the available alternative methodologies, the Social Vulnerability Index (*SoVI*) remains the most widely adopted approach in research studies. In Europe, research has generally followed two complementary trajectories: (1) the adaptation of *SoVI* indices to local or national contexts, and (2) the integration of social indicators with physical seismic hazard models to produce spatially explicit risk maps. In Southeastern Europe, one of the earliest applications of social vulnerability mapping to earthquakes was carried out in Bucharest, Romania. Armaş (2012) developed a multivariate model combining census indicators with building data to evaluate urban districts' susceptibility to seismic damage. The results showed that social vulnerability was closely aligned with the spatial distribution of old housing stock and low-income populations, demonstrating that the human component of risk could be systematically mapped. A subsequent study by Armaş and Gavriș (2013) refined this approach, comparing a locally developed Seismic Vulnerability Index (SEVI) with *SoVI*. They concluded that both indices identified similar clusters of vulnerability but differed in sensitivity to data normalisation and variable weighting-an issue echoed by Schmidtlein et al. (2008) and Tate (2012), who emphasised that methodological choices can substantially alter vulnerability rankings.

Across the extended Mediterranean basin, *SoVI*-related approaches have been used to capture the social dimension of earthquake risk. Fekete (2009) examined vulnerability indicators for hazard-prone regions of Central Europe, underlining the need for harmonised metrics to enable cross-country comparison. In the broader European context, Tapsell et al. (2010) reviewed social vulnerability frameworks for natural hazards, identifying socioeconomic status, age, and disability as consistently significant predictors of disaster impact and recovery potential. These findings informed subsequent European initiatives such as the MOVE (Methods for the Improvement of Vulnerability Assessment in Europe) project, which proposed a conceptual model integrating physical, social, economic, and environmental vulnerability (Birkmann et al., 2013). More recently, Cerchiello et al. (2018) and Rodriquez et al. (2018) applied the *SoVI* approach to characterise social vulnerability in the particularly challenging context of Palestine, confirming both the need to include social vulnerability in integrated seismic risk studies and its correlation with specific building taxonomy groups.

For what concerns the countries of the EMERGE cross-border case-study, in Greece, a country with high seismic hazard, vulnerability studies have increasingly incorporated social indicators alongside physical risk assessments. Lekkas et al. (2011) analysed the relationship between urban morphology, socioeconomic characteristics, and damage potential in Athens and Thessaloniki, highlighting that older housing stock and socio-economically disadvantaged districts were more exposed to earthquake losses. More recently, Komac et al. (2014) and Fekete et al. (2017) included Greece in comparative European analyses of disaster vulnerability, underlining regional disparities in both hazard exposure and adaptive capacity. These works collectively demonstrate that within high-hazard zones, social inequality, ageing populations, and urban density patterns act as critical amplifiers of seismic risk.

Similar patterns emerge across the Western Balkans, where rapid urban growth and socio-economic disparities influence seismic risk. In Albania, systematic social vulnerability assessment remains relatively recent but gained momentum following the 2019 Durrës earthquake. The Post-Disaster Needs Assessment (PDNA) led by the World Bank, the European Union, and the United Nations (World Bank and European Commission, 2020) identified housing quality, informality in construction, and socioeconomic deprivation as key drivers of uneven losses and delayed recovery. The PDNA explicitly recommended the development of a national vulnerability index to inform reconstruction and future risk reduction. Similarly, research by Çelo et al. (2022) used census and building data to map multi-hazard vulnerability in Albania, noting that social conditions strongly modulate the physical hazard effects, particularly in coastal and peri-urban areas.

In North Macedonia, historical analyses (UNESCO, 1964; Spence et al., 2011) documented how rapid urbanization and informal housing expansion after the 1963 Skopje earthquake have created persistent social and infrastructural vulnerabilities. More recent works have applied GIS-based multicriteria methods to assess seismic risk at municipal level, combining hazard, exposure, building fragility, and demographic sensitivity (Markoski et al., 2017). These studies confirm that even moderate-magnitude earthquakes could cause significant social and economic disruption where older reinforced-concrete buildings coincide with lower-income populations.

Overall, the need to integrate physical and social dimensions is commonly accepted, also confirmed by more recent EU research projects. The RISK-UE project (Milutinović and Trendafiloski, 2003) and successive ones provided standardized methodologies for urban seismic risk scenarios, including modules on socioeconomic exposure. Subsequent European frameworks, such as the SERA and ESHM20 projects, expanded this integration by coupling hazard and exposure models with demographic datasets to support civil protection planning (Danciu et al., 2021). These initiatives have encouraged the adoption of multi-indicator approaches that treat social vulnerability as a quantifiable, mappable component of seismic risk, rather than an abstract social issue.

2. Methodology

The social vulnerability assessment was conducted using the Social Vulnerability Index (*SoVI*) framework originally proposed by Cutter et al. (2003), which quantifies the degree to which a population is susceptible to the adverse impacts of natural hazards based on a set of socio-economic and demographic indicators.

Within the EMERGE project, the *SoVI* approach was adapted to the cross-border region (CBR) encompassing Albania, North Macedonia, and Greece, comprising 17, 18, and 14 municipalities, respectively, for a total of 49 municipalities included in the study area (Figure 1). The selected variables were defined to reflect both the availability of reliable data and the socio-economic characteristics of the region. The *SoVI* framework was applied across these municipalities to capture differences in the capacity of neighboring municipalities in CBR to anticipate, withstand, and recover from earthquake impacts. Despite experiencing comparable seismic exposure, these municipalities demonstrate distinct patterns of loss and recovery driven by underlying social and institutional disparities.

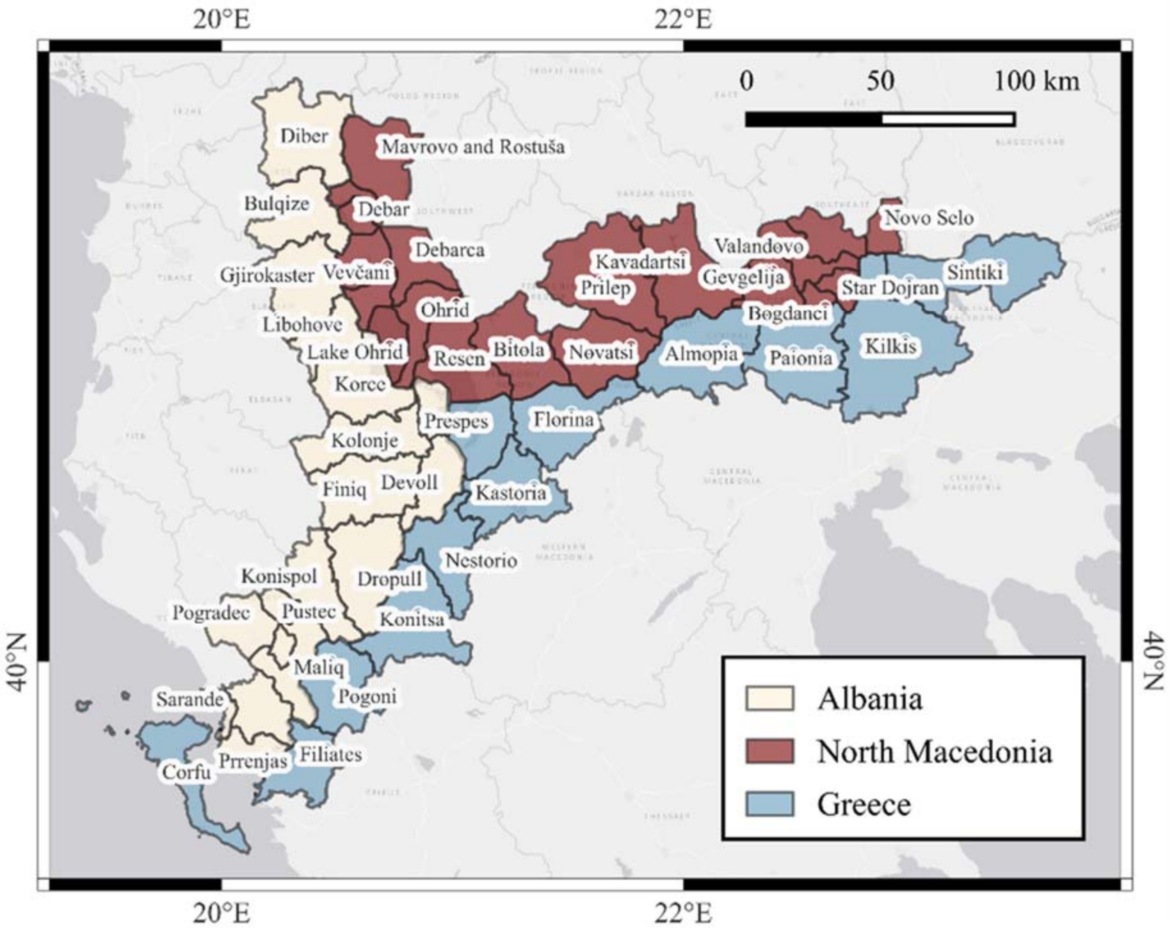


Figure 1. Cross-border region (CBR) between Albania, North Macedonia, and Greece considered for the SoVI analysis, showing the municipalities included in the study area.

Two main methodological approaches exist to assess the *SoVI*: the deductive and the inductive approach. The deductive approach relies on a predefined and limited set of variables based on established theoretical frameworks, while the inductive approach is data-driven, incorporating a wider range of socio-economic indicators for greater contextual flexibility. Given the increasing availability of detailed census and socio-economic data, the inductive approach was adopted in this work.

The first step in developing the *SoVI* for the EMERGE region involved defining the contextual and demographic conditions that characterise the target population, based on the social composition and socio-economic structure of each municipality. Relevant characteristics reflect the overall capacity of local populations across the key dimensions of preparedness, response, and recovery in the face of damaging seismic events.

Extensive research has demonstrated that communities experience and recover from disasters differently even under similar hazard exposure, depending on factors such as demographic structure, education, income equality, access to healthcare, and the availability of critical infrastructure. In the EMERGE cross-border context, these aspects are complemented by settlement patterns (urban–rural gradients) and governance quality, both of which strongly influence resilience at the municipal level.

Accordingly, the selected indicators were organized into seven thematic groups representing the main dimensions of social vulnerability:

- Population
- Education
- Economy
- Health
- Infrastructure
- Habitat
- Governance and Institutional Capacity

Each thematic group includes multiple indicators. The indicators were selected according to the local social context and the availability of census data. Once census and statistical data were collected, each indicator was normalized and statistically analysed to determine its contribution within the group, expressed through factor loadings or weights. The product of each indicator's value and its corresponding weight defines its contribution to the overall *SoVI* score at the municipal level. These datasets represent the underlying social conditions and may have positive or negative cardinality, indicating whether an increase in their value leads to a corresponding increase (+) or decrease (–) in social vulnerability. The complete set of indicators and their associated sub-indices is presented in Table 1, which also specifies the cardinality of each indicator. A detailed description of each indicator group and the corresponding sub-indicators adopted in this work is provided in the following sections.

Table 1. Group and sub-group Indicators for the computation of SoVI along with their Cardinality

No.	Group Indicator	No.	Indicator	Cardinality
1	*Population*	1	% Population < 18/19 years	+
		2	% Population > 60 years	+
		3	% Female	+
		4	% Disabled	+
		5	% Population of foreign nationality	+
2	*Education*	6	% Illiterate	+
		7	% Population without elementary education	+
		8	% Population without high school education	+
		9	% Population with high school degree	-
		10	% Population with university graduates	-
3	*Economy*	11	Unemployment rate	+

		12	% Labor force working in secondary sector employment	+
		13	% Labor force employed in service industries	+
		14	% Female labor force participation	+
		15	Average income	-
		16	% below poverty line	+
4	*Health*	17	# Hospitals	-
		18	# Beds	-
		19	# Doctors	-
		20	Crude birth rate	+
		21	Crude death rate	-
		22	Life expectance	-
		23	% Population covered by basic health system	+
5	*Infrastructure*	24	Road network (km/km^2)	-
		25	% House without water	+
		26	% House without electricity	+
		27	% Vehicles	-
6	*Habitat*	28	% Female headed households	+
		29	Population density (# people/ km^2)	+
		30	Housing density (# people /house)	+
		31	Urban density (# buildings/ km^2)	+
		32	% House owners	+
		33	% Urban population	-
7	*Governance And Institutional Capacity*	34	Crime rate	+
		35	Abstention rate from election	+

The ***Population*-related indicators** employed in this work describe key demographic characteristics that influence community vulnerability within the cross-border municipalities of Albania, Greece, and North Macedonia. These indicators capture population structure and social composition through five main variables: the percentage of individuals under 18/19 years of age, over 60 years of age, the female population, the population of foreign nationalities, and the percentage of residents with disabilities, as shown in Table 1. These demographic groups are generally more exposed to risk; thus, they show a positive cardinality (+), with higher proportions indicating greater social vulnerability. Elderly people and individuals with disabilities may experience mobility or health constraints that limit their ability to respond effectively to emergencies, while younger populations depend on social and institutional support systems. Moreover, women and foreigners often face economic or social inequalities that can exacerbate post-disaster vulnerability.

The ***Education*-related indicators** reflect a key dimension of social vulnerability, as education level is strongly associated with both economic resilience and adaptive capacity. Education influences income opportunities, access to information, and the ability to make informed decisions in the face of natural hazards. Populations with lower levels of education are generally more vulnerable, as they may have limited access to early warning systems, institutional support, and recovery resources. Conversely, higher educational attainment is associated with improved preparedness and enhanced communication within the community, fostering a more resilient and informed society. The herein selected indicators represent the distribution of education levels across five categories: *Graduated*, *High school*, *Diploma*, *Elementary*, and *Illiterate* for each municipality in Albania, Greece, and North Macedonia. These indicators were chosen for their representativeness and their significant contribution to understanding education as a determinant of social vulnerability.

The ***Economy*-related indicators** describe the financial capacity and employment structure of the municipalities in Albania, Greece, and North Macedonia, which play a fundamental role in determining community resilience and vulnerability. Economic well-being significantly affects the ability of populations to absorb losses and recover from the impacts of natural hazards. The selected indicators include the share of employment in *service industries* and *secondary sectors*, *unemployment rate*, *female labor force participation*, *poverty index*, and *per capita gross domestic product (GDP)*. In particular, municipalities with high unemployment and poverty levels, or limited participation of women in the workforce, are considered more vulnerable (positive cardinality (+)) due to restricted access to financial and institutional support. Conversely, areas with a stronger service sector and higher GDP per capita tend to exhibit lower economic vulnerability and greater adaptive capacity, hence these indicators are characterized by a negative cardinality (–). When detailed economic data were unavailable at the municipal scale, national-level statistics were used to ensure consistency and comparability across countries.

The ***Health*-related indicators** assess the accessibility and capacity of healthcare systems across the cross-border municipalities of Albania, Greece, and North Macedonia. Healthcare services, such as hospitals, medical personnel, play a crucial role in reducing vulnerability and ensuring rapid recovery following natural or social crises. The selected indicators include the *number of hospitals*, *available beds and doctors, crude birth and death rates*, *life expectancy*, and the *percentage of population covered by basic health services*. Indicators such as the number of hospitals, beds, and doctors are negatively correlated (–) with vulnerability, as higher availability of medical infrastructure and personnel enhances emergency response and recovery capacity. Similarly, higher life expectancy and greater population coverage by the basic health system reduce social vulnerability. Conversely, the crude birth rate presents a positive correlation (+), since higher birth rates can increase dependency ratios and strain healthcare and social support systems, particularly in areas with limited medical infrastructure. The crude death rate is negatively correlated (–). Most of these variables are normalized with respect to the 1000 inhabitants to ensure comparability among municipalities of different sizes.

The ***Infrastructure*-related indicators** capture the accessibility and quality of essential services and facilities. Access to utilities such as piped water, electricity, and transportation networks plays a critical role in reducing social vulnerability and improving post-disaster response. Well-developed infrastructure enables rapid evacuation, delivery of aid, and continuity of essential services, whereas inadequate access to utilities or road systems can significantly increase the risk and impact of disasters. The selected indicators include the *road network density (km/km^2)*, *percentage of houses without access to water and electricity*, and the *number of vehicles per person*. Most of these variables were normalized with respect to the total population or municipal area to ensure comparability across regions. Municipalities with limited transportation infrastructure or inadequate access to basic utilities tend to experience higher vulnerability levels, as these deficiencies hinder mobility, emergency logistics, and communication. Conversely, areas with denser road networks and full utility coverage are generally better equipped to manage and recover from hazardous events. All the infrastructure-related indicators are characterized by a positive (+) cardinality expect the road network and vehicle numbers.

The ***Habitat*-related indicators** describe the characteristics of the built environment and settlement patterns. The selected indicators include the *percentage of female-headed households*, *population density*, *housing and urban density*, *percentage of homeowners* and *share of urban population*. Highly dense urban areas may concentrate exposure and complicate evacuation procedures, while sparsely populated regions can face challenges in accessing essential services. Residential ownership, meanwhile, reflects financial stability and long-term attachment of households to their communities, influencing post-disaster recovery capacity. Accordingly, all habitat indicators generally show a positive cardinality (+), as higher population, housing, and urban densities tend to increase exposure and vulnerability, while house ownership and, in this study, urban population are considered to reduce vulnerability (–) due to their association with greater stability and better access to services. While in many developing contexts higher urbanization is often associated with increased vulnerability due to overcrowding, infrastructure stress, and social inequality, this is not the case for the municipalities in the examined cross-border region. Here, higher levels of urbanization generally correspond to better access to healthcare, transportation, and emergency services, thus reducing vulnerability.

The ***Governance*-related indicators** capture the institutional and social dimensions of vulnerability. Effective governance, citizen participation, and public security are essential components of community resilience. In this study, only two variables were considered: the *crime rate (per 100,000 inhabitants)* and the *abstention rate from elections*. The crime rate serves as a proxy for social stability and community safety, with higher values indicating potentially weaker institutional control and higher vulnerability. The abstention rate reflects the degree of civic engagement and trust in public institutions, key aspects that determine how effectively a community can organize, cooperate, and recover after a disruptive event.

The computation of the Social Vulnerability Index (*SoVI*) for the cross-border municipalities was based on this set of 35 census-based indicators derived from national census datasets and other official statistical sources for Albania, Greece, and North Macedonia. Census data were primarily obtained from national databases at the municipal level (e.g., INSTAT, ELSTAT, MAKSTAT), while equivalent sources such as Eurostat or national statistical agencies were used when municipal data were unavailable. In cases where disaggregated information was missing, national statistics or proxy variables with strong correlations to the unavailable indicators were employed to ensure comparability and spatial consistency across the cross-border area.

To ensure comparability among variables expressed in different measurement units, all indicators were normalized using a min–max normalization procedure, which removes scale effects and standardizes each indicator to a common range between 0 and 1. In this framework, 0 and 1 represent, respectively, the least and most socially vulnerable conditions. The raw census data were therefore collected, standardized, and transformed into comparable scales according to the min–max normalization procedure expressed in the following equation:

$$X_{q,i}^{N} = \frac{x_{q,i} - \min_i(x_q)}{\max_i(x_q) - \min_i(x_q)} \tag{1}$$

where $x_{q,i}$ represents the value of indicator *q* for municipality *i*, and $\min_i(x_q)$ and $\max_i(x_q)$ are the minimum and maximum values of the same indicator across all municipalities and $X_{q,i}^{N}$ is the normalized index score of indicator *q* for municipality *i*.

The vulnerability score (V_i) for each municipality *i* was obtained by aggregating the normalized values of each indicator *q*, applying their corresponding weights, and rescaling the results to a range between 0 and 5 (*S*), where 0 represents the least vulnerable and 5 the most vulnerable conditions, according to the following equation:

$$V_i = S\sum_{q=1}^{n} w_q X_{q,i}^{N} \tag{2}$$

where w_q is the weight assigned to the q^{th} indicator and *n* is the total number of variable/indicators considered.

Since it is a relative measure, *SoVI* provides comparative scores within the specific geographic extent considered in the analysis.

Following data collection and normalization, the indicators were analysed to determine their relative contribution within each thematic dimension through factor loadings. To improve the robustness and representativeness of the index, weights were assigned to each indicator according to two main criteria:

- *Importance of the data*, reflecting the theoretical relevance of each indicator to social vulnerability;
- *Quality of the data*, capturing the reliability, completeness, and spatial resolution of the available information.
-

These weighting criteria ensure that variables with higher conceptual importance and better data quality exert proportionally greater influence on the final *SoVI* score.

Table 2: Weights for the importance and quality of data assigned to each indicator or variable belonging to the respective thematic groups of the Social Vulnerability Index (SoVI) for Greece, North Macedonia, and Albania. The table also indicates the administrative level at which each variable is available (M = municipality, P = prefecture, R = regional, C = country)

Group	**No.**	**Indicator**	**LEVEL (e.g. M=municipality, P=prefecture, R=regional, C=country)**			**Importance**			**Quality of data**		
			GR	**MK**	**AL**	**GR**	**MK**	**AL**	**GR**	**MK**	**AL**
Population	1	% Population < 18/19 years	M	M	M	0.250	0.300	0.200	0.210	0.200	0.200
	2	% Population > 60 years	M	M	M	0.300	0.250	0.250	0.210	0.200	0.200
	3	% Female	M	M	M	0.050	0.050	0.050	0.210	0.200	0.200
	4	% Disabled	C	M	M	0.300	0.350	0.350	0.160	0.200	0.200
	5	% Population of foreign nationality	M	M	M	0.100	0.050	0.050	0.210	0.200	0.200
Education	6	% Illiterate	M	M	M	0.400	0.400	0.400	0.400	0.400	0.400
	7	% Population without elementary education	M	M	M	0.300	0.300	0.300	0.300	0.300	0.300
	8	% Population without high school education	M	M	M	0.200	0.200	0.200	0.200	0.200	0.200
	9	% Population with high school degree	M	M	M	0.100	0.100	0.100	0.100	0.100	0.100
	10	% Population with university graduates	M	M	M	0.000	0.000	0.000	0.000	0.000	0.000
Economy	13	% Labor force employed in service industries	M	M	P	0.100	0.150	0.100	0.175	0.200	0.180
	12	% Labor force working in secondary sector employment	M	M	P	0.100	0.200	0.100	0.175	0.200	0.180
	11	Unemployment rate	M	M	P	0.250	0.250	0.250	0.175	0.200	0.180
	14	% Female labour force participation	M	M	P	0.050	0.050	0.050	0.175	0.200	0.180
	16	% Below poverty line	C	C	C	0.250	0.150	0.300	0.150	0.100	0.100

	15	Average family income	P	C	P	0.250	0.250	0.200	0.150	0.100	0.180
Health	17	# Hospitals	M	M	M	0.150	0.150	0.150	0.167	0.160	0.190
	18	# Beds	M	M	C	0.150	0.150	0.150	0.167	0.160	0.100
	19	# Doctors	P	M	C	0.150	0.150	0.150	0.167	0.160	0.100
	20	Crude birth rate	C	M	M	0.100	0.100	0.100	0.125	0.160	0.190
	21	Crude death rate	C	M	M	0.150	0.150	0.150	0.125	0.160	0.190
	22	Life expectance	C	C	P	0.150	0.150	0.100	0.125	0.100	0.130
	23	% Population covered by basic health system	C	C	C	0.150	0.150	0.200	0.125	0.100	0.100
Infrastructure	24	Road network (km/km^2)	M	M	M	0.267	0.267	0.267	0.250	0.400	0.250
	25	% House without water	M	C	M	0.267	0.267	0.267	0.250	0.100	0.250
	26	% House without electricity	M	C	M	0.267	0.267	0.267	0.250	0.100	0.250
	27	% Vehicles	M	M	M	0.200	0.200	0.200	0.250	0.400	0.250
Habitat	28	% Female headed households	M	M	M	0.167	0.167	0.167	0.167	0.167	0.167
	29	Population density (#people/ km^2)	M	M	M	0.167	0.167	0.167	0.167	0.167	0.167
	30	Housing density (# people /house)	M	M	M	0.167	0.167	0.167	0.167	0.167	0.167
	31	Urban density (#buildings/ km^2)	M	M	M	0.167	0.167	0.167	0.167	0.167	0.167
	32	% House owners	M	M	M	0.167	0.167	0.167	0.167	0.167	0.167
	33	% Urban population	M	M	M	0.167	0.167	0.167	0.167	0.167	0.167
Governance And Institutional Capacity	34	Crime rate	R	C	P	0.600	0.500	0.700	0.400	0.300	0.400
	35	Abstention rate from election	M	M	M	0.400	0.500	0.300	0.600	0.700	0.600

The final weight assigned to each indicator ($w_{q,i}$) within a given group q was obtained by combining the weights representing the importance ($w_{q,i,I}$) and quality of data ($w_{q,i,Q}$) according to the following equation:

$$w_{q,i} = \frac{w_{q,i,I} \cdot w_{q,i,Q}}{\sum_{i=1}^{n} (w_{q,i,I} \cdot w_{q,i,Q})} \qquad (3)$$

This procedure guarantees internal consistency among indicators and allows direct comparison between groups having a different number of variables.

A sensitivity analysis was subsequently conducted to evaluate the robustness of the *SoVI* results and to identify how the weighting scheme affects the final rankings. By systematically varying the weighting schemes, the analysis quantified the uncertainty associated with each Country-weight-methodological choice and revealed the relative influence of individual components of the *SoVI* outcomes. The composite *SoVI* value was obtained by aggregating the weighted vulnerability scores across all relevant thematic dimensions, producing an additive index that represents the overall social vulnerability of each municipality.

3. SoVI data

The Social Vulnerability Index (*SoVI*) was calculated for the municipalities shown in Figure 1, representing the cross-border area between Albania, Greece, and North Macedonia.

To ensure a robust and comparative assessment, two different analytical scenarios were developed based on the weighting schemes defined previously. **Scenario 1** adopts a common weighting scheme for the *"Importance"* category across all cross-border municipalities, while applying country-specific weights for the *"Quality of data."* In this case, only the *"Quality of data"* column is adjusted to reflect the variability and reliability of data sources within each country. **Scenario 2**, on the other hand, applies country-specific weights to both *"Importance"* and *"Quality of data."* This approach allows for a more context-sensitive analysis, accounting for national differences in both the perceived relevance of each indicator and the quality of the available data. By comparing the results of these two scenarios, the analysis highlights how varying the weighting schemes can influence the spatial distribution and interpretation of social vulnerability across the cross-border area

3.1. Albania

For Albania, the analysis for the Socio-Economic Vulnerability Assessment is mainly based on INSTAT (Albanian Statistical Authority) data. Most of these data are taken from CENS 2023, the last one conducted for our country, published in various reports at national or regional level. Based on these reports but also on the INSTAT official website (https://www.instat.gov.al/), detailed research was conducted to find municipal information and, in those cases, when local data were missing, regional ones were considered. For some data, mostly for indexes referring to Health and Infrastructure, alternative information sources are used also, such as planning and strategic documents for various services, or even international databases that provide information at the national level. In the following is given a summary information for each data set, providing specific clarifications mainly in cases when data are taken from alternative sources (not from INSTAT) or assumptions made in some cases when the data was not founded in the required format.

Population

All demographic data for calculating population indicators are obtained from INSTAT (CENS 2023) at the municipality level.

Education

For the education-related data, CENS 2023 considers the resident population aged 10 years and above for each municipality. The dataset includes several educational attainment categories, defined as follows: individuals who never attended school; those with no level of education completed, referring to residents who started but did not finish elementary school; individuals who completed primary school (classes 1–4); those who attended lower secondary school (up to classes 7/8/9); individuals who completed upper secondary school (i.e., high school, up to class 12); and finally, individuals with tertiary or postgraduate education, covering both university and post-university studies. These categories provide a structured basis for constructing the educational indicators used in the vulnerability analysis.

For the calculation of the educational indexes (in %), based on the CENS 2023 data, several assumptions were made to ensure consistency across categories. The percentage of illiterate population was estimated as the sum of individuals who never attended school and inhabitants aged 0–10 years, divided by the total population. The population without elementary education was calculated as the proportion of individuals with no level of education completed over the total number of inhabitants. The percentage of population with basic education corresponds to those who completed primary school and lower secondary school (up to classes 7/8/9), divided by the total population. The population with a high school degree was obtained by dividing the number of individuals with upper secondary education by the total population. Finally, the population with university education includes individuals holding tertiary or postgraduate degrees, expressed as a percentage of the total inhabitants. The sum of all educational index categories equals 100%, ensuring a complete representation of the population's educational structure.

Economy

Economic indicators, including employment sectors, unemployment rates, and women's labor force participation, were retrieved from INSTAT at the regional level. The only exception was the % poverty that is given at country level.

Health

Health-related indicators were primarily obtained from national strategic planning documents approved recently by the Decision Council of Ministers (DCM) and INSTAT. Below are presented the respective sources for each indicator:

The number of hospitals and the number of beds (per 1000 inh.) are taken from DCM no. 118, dated 01.03.2023 "On the approval of the national hospital plan 2023–2030". For no. of hospital are referred regional or municipal hospitals for each municipality while for the number of beds (per 1000 inh.) is accepted the national value of 3.7 beds / 1000 inhabitants. The number of doctors (per 1000 inh.) is taken from DCM no. 210, dated 06.04.2022 "On the approval of the Health Care National Strategy 2021-2030". Again, this data is given at national scale, that is accepted the same for each municipality, and it is 1.93 doctors per 1000 inhabitants. The indicators "*Crude birth rate*" and "*Crude death rate*" are calculated based on INSTAT data for 2023 at municipal level, while "*Life expectancy*" is referred at regional level from "Regional Statistical Yearbook 2023". For "*% population covered by basic health system*", data are taken from World Development Indicators (World Bank, 2023) referring to UHC (Universal Health Care) service coverage index, that in case of Albania was 64%.

Infrastructure

Infrastructure indicators included access to piped water, electricity, and transportation networks. Data on households without access to water and electricity were collected from INSTAT, while the road network density was computed directly from OpenStreetMap (OSM) data, normalized by the total municipal area to obtain a comparable indicator across municipalities.

Habitat

Habitat-related indicators such as housing and population density, urban density, home ownership, and average area per census unit were derived from INSTAT housing and population census data at the municipality level for 2023. These datasets allowed the characterization of both urban and rural settlement patterns relevant to vulnerability assessment.

Governance and Institutional Capacity

Governance indicators included the crime rate and abstention rate from elections. The data for abstention rate was directly obtained from the Central Election Commission official web page (https://kqz.gov.al/home). Abstention rate refers to the last parliamentary election in 2025.

The source data to calculate the crime rate are taken from the "2024 Yearly Report of the General Persecutor's Office". Referring to this document, the country's crime rate (on 100000 inhabitants) based on all criminal proceedings registered for 2024 is 1037. While the regional crime rates, for those regions that include municipalities part of the cross-border area, are the following: Dibër [536], Elbasan [672], Korçë [1005], Gjirokastër [1268], Sarandë [2140].

As agreed, the crime rates referred to the SoVI table consider crimes against life and health that consist of 2.2% of all crimes registered. Both indicators were used as proxies for social stability and institutional performance.

3.2. Greece

For Greece, all data used in the Social Vulnerability Index (SoVI) analysis were collected primarily from ELSTAT (Hellenic Statistical Authority) at the municipality level, ensuring consistency across most indicators. Complementary sources included official government databases and open-access platforms such as OpenStreetMap (OSM) for infrastructure-related information. The following subsections summarize the data collection and processing steps for each indicator category. The majority of the data refers to the latest available census 2021 while in some cases data from 2011 were accessed.

Population

Demographic indicators, including population density and gender composition, were obtained from ELSTAT at the municipality level. Information on people with disabilities was available only at the national level; therefore, national ratios were applied uniformly to the municipal populations.

Education

Educational attainment indicators, such as the percentage of graduates, high school and elementary education levels, and illiteracy rates, were collected directly from ELSTAT at the municipality level. These data provided a detailed view of educational profiles across the country.

Economy

Economic indicators, including employment sectors, unemployment rates, and women's labor force participation, were retrieved from ELSTAT at the municipality level. The only exception was the monthly salary income, which was available at the prefecture level; this variable was therefore assigned to all municipalities within the corresponding prefecture. The per capita Gross Domestic Product (GDP) was also used as a complementary measure of economic capacity.

Health

Health-related indicators were primarily obtained from the Ministry of Health System and ELSTAT. The number of hospitals was extracted from national health databases, while the number of doctors was originally available only at the prefecture level. In this case, a proxy-based interpolation was performed using the municipal population as a weighting factor to estimate the distribution of doctors per municipality. For life expectancy, data were reported separately for males and females at the national level. The expected life expectancy for each municipality was calculated as a weighted average, proportional to the local male-to-female population ratio. Similarly, the crude birth rate and crude death rate were available only at the country level, and thus uniformly applied across municipalities.

Infrastructure

Infrastructure indicators included access to piped water, electricity, and transportation networks. Data on households without access to water and electricity were collected from ELSTAT, while the road network density was computed directly from OpenStreetMap (OSM) data, normalized by the total municipal area to obtain a comparable indicator across municipalities.

Habitat

Habitat-related indicators such as housing and population density, urban density, home ownership, and average area per census unit were derived from ELSTAT's housing and population census data at the municipality level. These datasets allowed the characterization of both urban and rural settlement patterns relevant to vulnerability assessment.

Governance and Institutional Capacity

Governance indicators included the crime rate and abstention rate from elections. The abstention rate was directly obtained from official electoral statistics (Ministry of interior) at the municipality level, while the crime rate was sourced from governmental records of the Hellenic Police. Both indicators were used as proxies for social stability and institutional performance.

3.3. North Macedonia

For North Macedonia, all data used in the Social Vulnerability Index (*SoVI*) analysis were collected primarily from MAKSTAT database (State Statistical Office of Republic of Nort Macedonia)) at the municipality level, ensuring consistency across most indicators. Complementary sources included official government databases, such as Institute for Public Health, Health Insurance Fund, State Election Commission, CRISIS project etc. and other sources (as IZIIS internal database) for infrastructure-related information. The following subsections summarize the data collection and processing steps for each indicator category. The majority of the data refers to the latest available census 2021.

Population

All demographic indicators, as listed in Table 1 under this group indicator were obtained from MAKSTAT database at the municipality level.

Education

Educational attainment indicators, such as the percentage of graduates, high school and elementary education levels, and illiteracy rates, were collected from MAKSTAT database at the municipality level. These data provided a detailed view of educational profiles across the country.

Economy

Economic indicators, including unemployment rate, labor force working in secondary sector employment, labor force employed in service industries and female labor force participation, were retrieved from MAKSTAT database at the municipality level. Average monthly income and below poverty line indicator were collected from the MAKSTAT database also but at the country level. The per capital Gross Domestic Product (GDP) was also used as a complementary measure of economic capacity.

Health

Health-related indicators, such as number of hospitals, number of doctors and number of beds were extracted from Institute of public health, at municipality level. The crude birth rate and crude death rate were retrieved from the MAKSTAT database at municipality level. Life expectancy was taken from WHO (2020) at country level and population covered by basic health system from the national insurance fund at country level.

Infrastructure

Infrastructure indicators included access to piped water, electricity, and transportation networks. All data were collected from MAKSTAT database at municipality level, except the road network density which was retrieved from CRISIS project.

Habitat

All six habitat related indicators were collected from MAKSTAT database at municipality level. For female headed households those with children were included. These datasets allowed the characterization of both urban and rural settlement patterns relevant to vulnerability assessment.

Governance and Institutional Capacity

Governance indicators included the crime rate and abstention rate from elections. The crime rate was sourced from MAKSTAT database at country level while abstention rate from elections was collected from State election commission at municipality level.

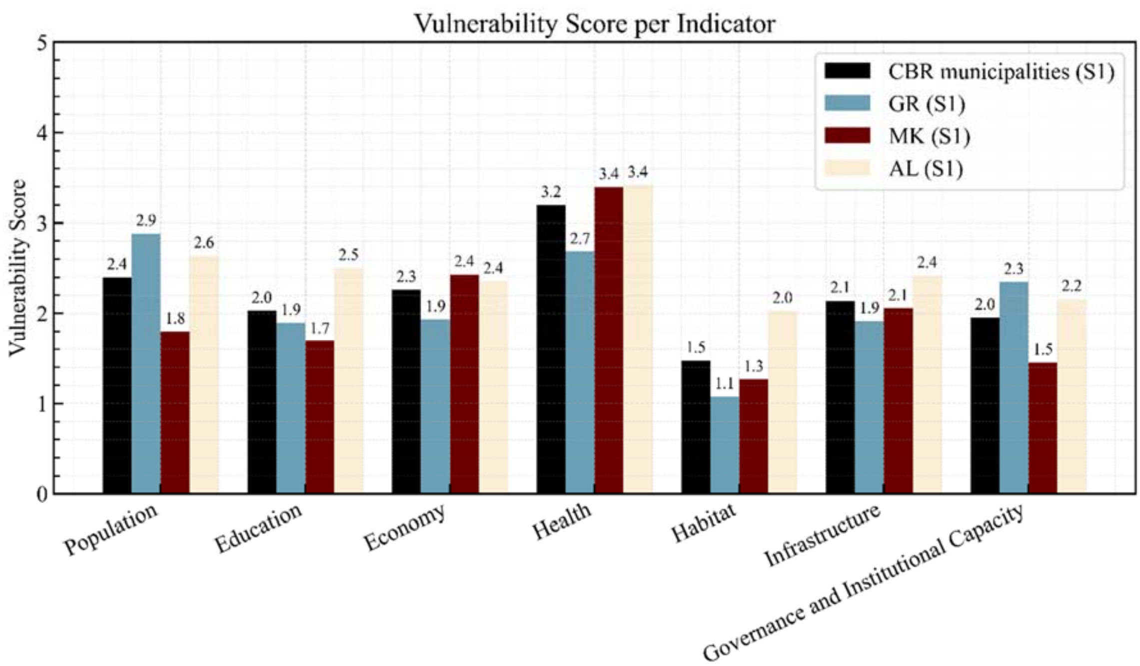
4. Results

All sub-indicators are transformed through the min–max normalization, which not only converts heterogeneous variables into comparable percentage-based values regardless of their original measurement units, but also rescales them relative to the minimum and maximum values observed across all municipalities within the study CBR area. In this way, for example, a poverty rate of 0.2 (20%) is not interpreted in absolute terms but expressed as a normalized score between 0 and 1 based on how it compares to the full range of values observed in the dataset.

The vulnerability score (V_i) for each group, computed according to Eq. (2) for every municipality, was subsequently averaged across all municipalities within the CBR study area, as well as for the municipalities belonging to each individual country. The following section discusses the results presented in Figure 2, which displays the *SoVI* values for each country under the two analyzed scenarios, distinguishing the outcomes across the different indicator groups.

Focusing on the *Population* indicator, in both scenarios Greece presents the highest vulnerability. This outcome is mainly driven by the high percentage of people with disabilities, approximately 10%, which is considerably higher than in the other cross-border countries. Since this variable is defined at the national level, it remains constant across all Greek municipalities, consistently influencing the overall indicator. In Scenario S1 the importance (in terms of percentage and weight) of this variable is strong enough to dominate the aggregated score, leading to Greece's highest Population-related vulnerability. In the second approach (Scenario S2), the weighting scheme reflects country-specific priorities, and the importance weight assigned to the disability variable is slightly lower. As a result, the overall index for Greece decreases slightly, although it still remains the highest among the compared countries. A similar trend is observed for Albania, where the percentage of people with disabilities ranges between 2% and 11%; however, the greater variability among municipalities leads, when averaged across the country, to slightly lower vulnerability values compared to Greece.

(a)



(b)

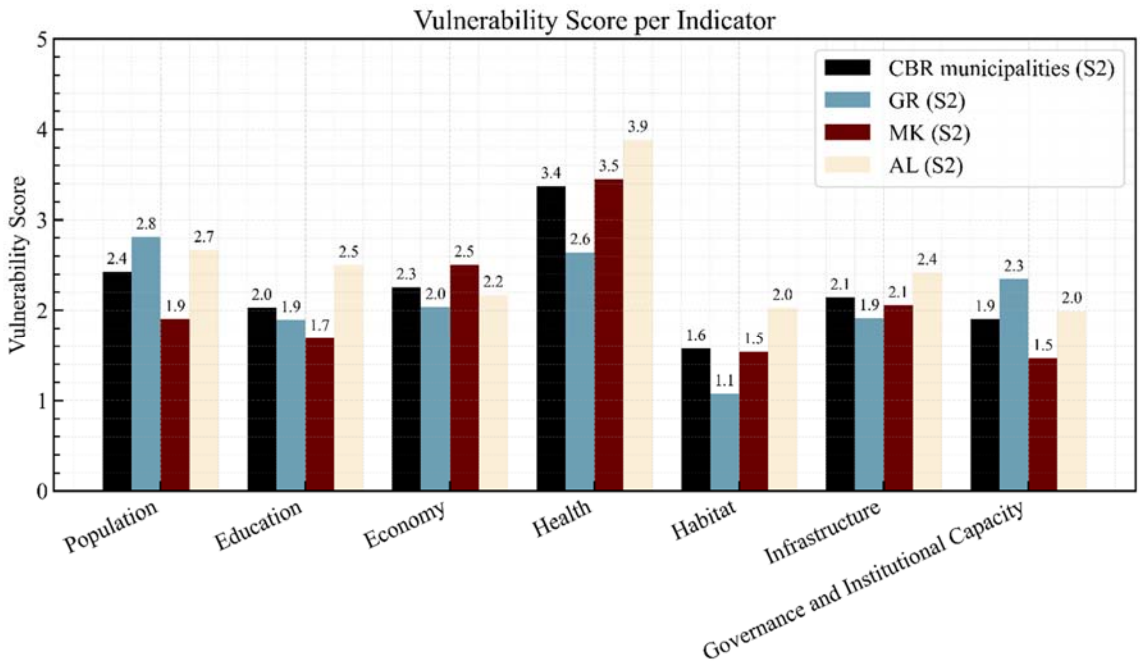


Figure 2: Average vulnerability scores within municipalities of CBR (black), Greece (blued), North Macedonia (red) and Albania (white) per indicator for (a) Scenario S1 and (b) Scenario S2.

For the *Education* indicator, the two approaches (Scenario S1 and Scenario S2) assign identical weights to the underlying sub-indicators. As a consequence, the resulting vulnerability patterns remain unchanged between the two weighting schemes. In both cases, Albania exhibits the highest educational vulnerability. This outcome is primarily driven by the distribution of educational attainment levels observed in the dataset: a higher proportion of individuals with lower formal education and a lower percentage of university graduates compared to the other countries.

With respect to the *Economy* indicator, North Macedonia systematically exhibits the highest vulnerability across both scenarios. This outcome is driven by (i) larger normalized percentages associated with employment in the secondary economic sectors and (ii) higher unemployment rates relative to the other countries considered. In Scenario S2, this effect becomes even more pronounced because these two sub-indicators are assigned higher weights, thereby amplifying their contribution to the aggregated economic vulnerability score. Although the same pattern is observed in Scenario S1, the difference in weighting is smaller, resulting in a less pronounced, but still dominant vulnerability score for North Macedonia. Consequently, the combined influence of higher values and reinforced weighting leads North Macedonia to consistently rank as the most vulnerable in the economic dimension.

The *Health* indicator shows the highest vulnerability levels among all dimensions considered, highlighting persistent disparities in healthcare provision across the cross-border area. The elevated values reflect the generally lower availability of hospitals, doctors, and hospital beds compared to national averages, typical of peripheral border regions. In Scenario S1, the vulnerability score for Health reaches 3.2 for CBR municipalities, 2.7 for Greece, and the highest values of 3.4 for both North Macedonia and Albania. In Scenario S2, all values increase slightly, with 3.4 for CBR municipalities, 2.6 for Greece, 3.5 for North Macedonia, and a peak of 3.9 for Albania.

A key factor behind Albania's particularly high vulnerability is the limited health system coverage, as only about 64% of the population is covered by the basic healthcare system, leaving a substantial portion without adequate access to essential services. This structural gap makes Albania notably more exposed in terms of public health. In Scenario S2, this variable was assigned a higher importance weight, which further accentuated Albania's health-related vulnerability. The persistence of this pattern across both scenarios confirms that the weighting adjustments reinforce existing disparities rather than altering the overall ranking, underlining Albania and North Macedonia as the most critical cases in terms of healthcare vulnerability.

The *Infrastructure* indicator shows moderate vulnerability levels across all countries, with values ranging between approximately 2.0 and 2.4 on the normalized scale. In both scenarios, Albania exhibits the highest infrastructure-related vulnerability, while Greece and North Macedonia display similar, slightly lower scores. This outcome reflects the generally lower availability and quality of infrastructure in the Albanian cross-border municipalities, particularly in terms of transport connectivity, road density, and utility coverage compared to the other areas analyzed. No significant differences are observed between Scenario S1 and Scenario S2, as the weighting structure remains relatively stable.

For the *Habitat* indicator, the results highlight clear differences among the three countries. Overall, Albania shows the highest vulnerability levels, primarily influenced by higher population and housing densities, combined with lower percentages of home ownership and smaller average living areas. North Macedonia presents intermediate conditions, where the combination of moderately high urban density and limited rural population contributes to increased vulnerability in certain areas. Greece, on the other hand, tends to exhibit lower vulnerability values, reflecting more favorable housing conditions and higher home ownership rates, though moderate vulnerability persists in municipalities with denser settlement patterns.

While the weights attributed to the sub-indicators are similar between the two approaches, the normalization method still affects the relative positioning of countries. Under the cross-border normalization (Scenario S1), Greek municipalities appear less vulnerable when compared with the broader regional context. In contrast, in the country-specific normalization (Scenario S2), the internal disparities within Albania become more pronounced, revealing higher relative vulnerability in its most urbanized environments.

The *Governance and Institutional Capacity* reflects moderate levels across all countries in the cross-border area. Since the indicator is based on only two variables, crime rate and electoral abstention, the influence of each variable is substantial, and even relatively small differences in the underlying data are enough to produce visible variations in the final scores. In Scenario S1, where both variables are assigned equal importance, the differences between countries are more contained. Vulnerability values range from 1.8 in North Macedonia to 2.4 in Greece, with Albania at 2.2 and the CBR municipalities at 2.1. The uniform weighting scheme in S1 tends to smooth out disparities, resulting in a more homogeneous distribution of scores. In Scenario S2, although the overall pattern remains similar, the expert-based weighting introduces slightly larger contrasts: Greece again shows the highest value (2.4), followed by CBR municipalities (2.1), Albania (2.0), and North Macedonia (1.9). Here, the differentiation arises not only from the underlying data but also from the fact that experts attributed different levels of importance to the two variables, amplifying the relative influence of the one deemed more critical.

The variations observed between scenarios highlight how both the data and the weighting approach shape the final outcomes. Depending on the indicator group considered, different countries emerge as more or less vulnerable, reflecting the diverse structural and socio-economic characteristics of each national context within the cross-border area.

Having analyzed the disaggregated vulnerability results for each country and indicator group under the two different approaches, it is now worthwhile to examine how the overall *SoVI* varies across the entire cross-border area, considering the combined contribution of all indicators to the total vulnerability. Figure 3 presents the spatial distribution of the Social Vulnerability Index (*SoVI*) across all cross-border municipalities for the two analyzed approaches, S1 and S2. In both configurations, the maps illustrate the relative level of vulnerability based on the aggregated indicator scores calculated for each municipality and averaging the vulnerability among all the indicator group. The general spatial pattern shows higher vulnerability values concentrated along the southern and central parts of the study area, particularly within Albanian and North Macedonian municipalities.

a)

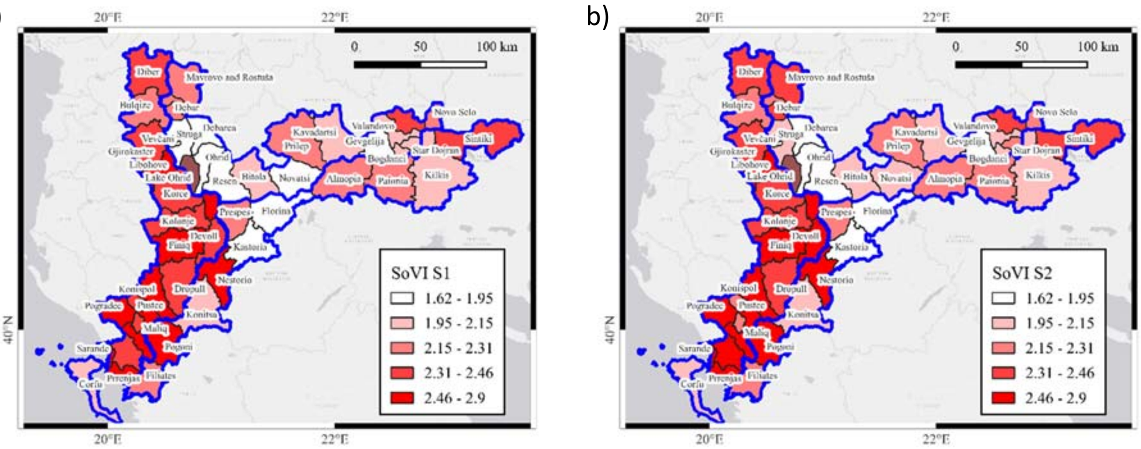


Figure 3. Spatial distribution of the Social Vulnerability Index (SoVI) for cross-border municipalities under the two approaches: (a) Scenario S1 with uniform indicator weights, and (b) Scenario S2 with country-specific weighting based on expert judgment.

When comparing the two scenarios, only minor spatial variations can be observed. The S2 configuration introduces differentiated weights reflecting country-specific priorities and expert judgment, leading to slightly higher *SoVI* values in some Albanian municipalities (e.g., Permet, Kolonje). Nevertheless, the overall pattern remains consistent, indicating that the regional structure of social vulnerability is robust and primarily driven by underlying demographic and infrastructural disparities rather than by the weighting scheme itself.

This type of assessment is particularly valuable at the governmental level for defining action priorities, namely identifying where to intervene first to evaluate and reduce social seismic risk. To this end, municipalities are plotted in descending order of their vulnerability scores: those on the left side of the graph represent the most vulnerable areas and could thus be considered priority targets for intervention (Figure 4). The bars are color-coded according to the country to which each municipality belongs, and the same visualization is presented for both Scenario S1 and Scenario S2.

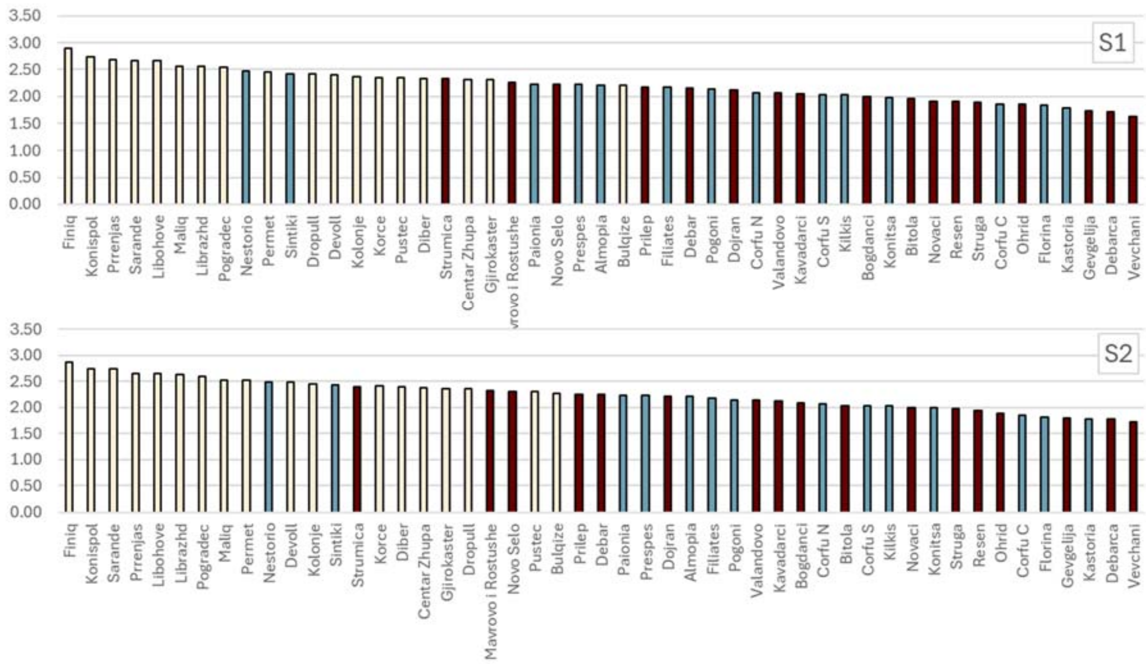


Figure 4. Cross-border municipalities sorted in descending order of Social Vulnerability Index (SoVI) score under (a) Scenario S1 and (b) Scenario S2. Bars are colored according to the country of each municipality.

As shown, Albanian municipalities generally exhibit the highest *SoVI* values, confirming their overall greater social vulnerability in both scenarios. However, the ranking order varies noticeably between S1 and S2, as the application of country-specific weights changes the relative position of several municipalities within each national context. In Albania, for instance, some municipalities such as Prrenjas, Sarande and Libohove shift their position but remain among the most vulnerable. Similarly, in Greece, Nestorio continues to rank high, although other municipalities move up or down in the list. In North

Macedonia, Mavrovo-Rostuša and nearby municipalities also change position depending on the scenario.

Overall, the figure illustrates that while the general cross-country pattern remains stable, the internal ranking within each country is sensitive to the weighting approach adopted, highlighting the impact of national-specific factors on the final vulnerability outcomes.
Following the same reasoning, Figure 5 presents the Social Vulnerability Index (SoVI) values for all cross-border municipalities under the two weighting schemes, S1 and S2. Municipalities are ordered in descending order according to their S1 values (solid bars) within each country, allowing for direct comparison with the S2 results (dashed-outline bars). The analysis shows that the largest differences between the two weighting schemes occur in North Macedonia, where several municipalities — such as Bogdanci, Dojran, Novaci, Bitola, Strumica, and Centar Zhupa, display the most pronounced variations, with differences approaching 0.09–0.10 in their SoVI values. These shifts suggest that the application of country-specific weights in Scenario S2 notably reshapes the internal ranking of North Macedonian municipalities.

In contrast, Albanian municipalities (e.g., Dropull, Kolonjë, Devoll) and Greek municipalities (e.g., Nestorio, Sintiki) exhibit more limited changes, typically below 0.05. Overall, this comparison indicates that while the country-specific weighting scheme (S2) only slightly modifies the broader cross-country pattern, it significantly affects the internal ranking of municipalities in North Macedonia, emphasizing the sensitivity of *SoVI* outcomes to national weighting adjustments.

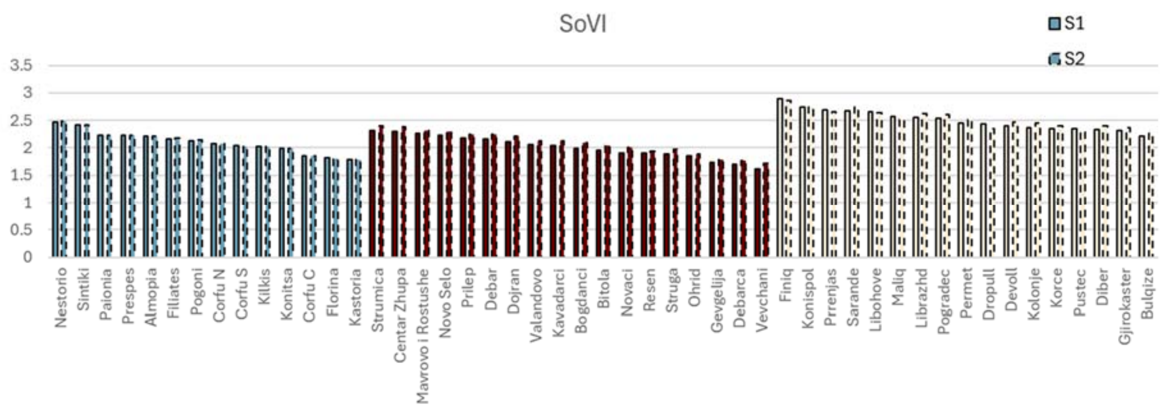


Figure 5. Comparison of SoVI values under Scenarios S1 and S2 for all cross-border municipalities, grouped by country. Municipalities are ordered by country and plotted with S1 and S2 values side by side. The results show that Albanian municipalities generally exhibit higher vulnerability levels, while differences between the two approaches remain smaller for Greece and North Macedonia.

To better visualize the effect of the weighting scheme, Figure 6 presents the spatial distribution of the differences between the SoVI values obtained under the two approaches (S1–S2). The map highlights the municipalities where the introduction of country-specific weights led to the largest changes in the overall vulnerability score. The results clearly show that Albanian municipalities exhibit the highest differences, particularly along the southern and central parts of the country. These areas experienced a notable increase in SoVI when local weighting was applied, confirming that the vulnerability of Albanian municipalities is more sensitive to the weighting structure than that of Greek or North Macedonian regions. Overall, the figure emphasizes that while the general vulnerability pattern remains consistent, the magnitude of change between S1 and S2 is greatest in Albania, reflecting stronger internal disparities in its social indicators.

In contrast, Greek municipalities display minimal changes, typically below 0.02, suggesting a greater internal consistency between the two weighting schemes. Overall, the figure illustrates that while the spatial pattern of vulnerability remains broadly consistent, the magnitude of change between S1 and S2 is greatest in North Macedonia, where the *SoVI* values appear more sensitive to the adoption of country-specific weights and the relative importance assigned to the underlying social indicators.

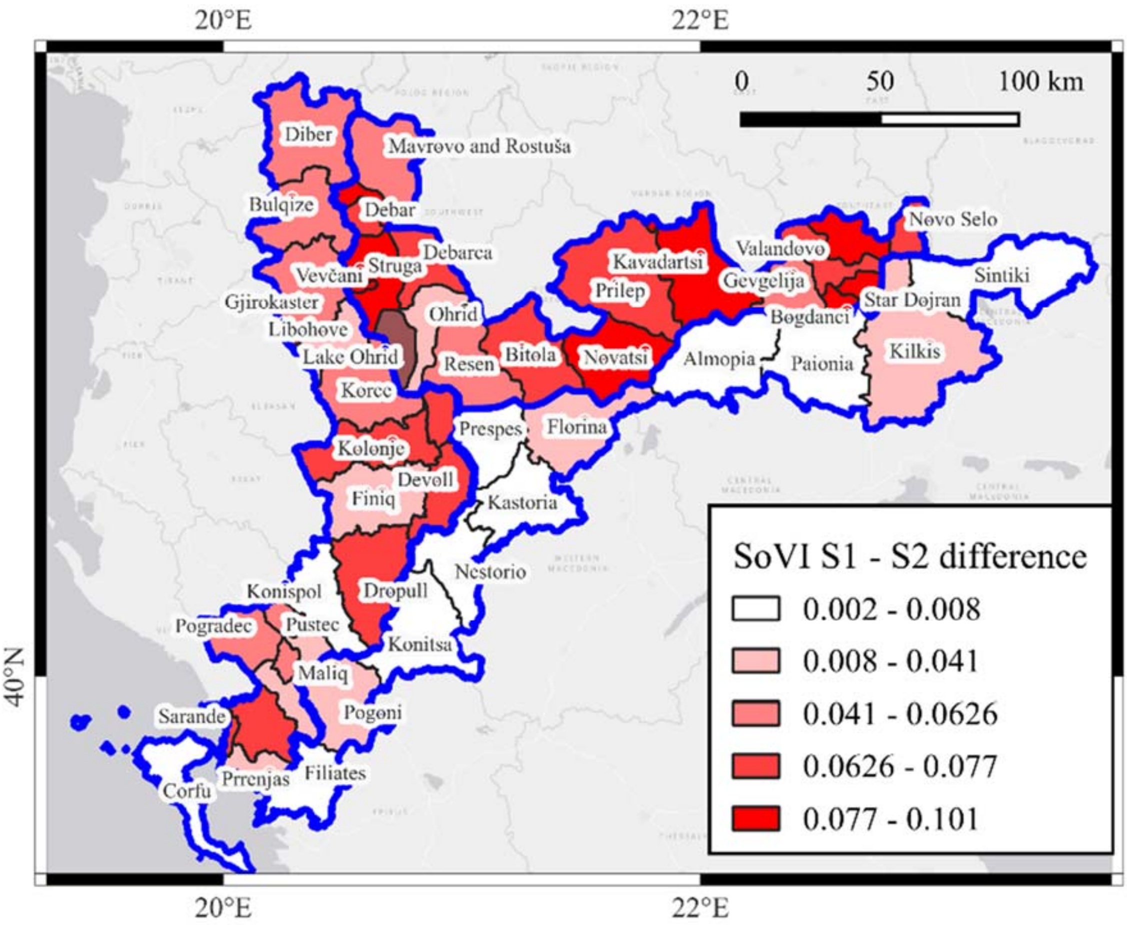


Figure 6. Spatial distribution of the difference between SoVI values obtained under Scenarios S1 and S2. The largest variations occur in Albanian municipalities, where the application of country-specific weights produces higher sensitivity and greater changes in vulnerability scores compared to Greece and North Macedonia.

5. Discussion and Conclusions

This analysis provides valuable insights into which thematic groups most strongly influence the vulnerability of each municipality and of each country's CBR as a whole. By distinguishing the relative contribution of social, demographic, and institutional dimensions, it becomes possible to identify where and why specific areas are more exposed to social vulnerability, thereby supporting the definition of targeted intervention priorities.

Uncertainties related to the relative weight of each variable within a thematic group, that is, its *importance*, as well as to the spatial resolution (whether provided at the municipal, regional, prefectural, or national level) of the available data, i.e. *quality*, were explicitly considered through the implementation of different weights finally combined in two different scenarios (S1 and S2).

These scenarios combine specific weights in alternative ways, leading not only to variations in the overall results but, more importantly, to a change in the ranking order of several municipalities. This shift directly affects potential decision-making processes, particularly in terms of prioritizing municipalities for policy actions or risk reduction measures.

One of the most important discussion points concerns the cross-border context in which this analysis was carried out. The objective was to highlight how areas that share similar geographical and environmental conditions, but belong to different countries, can still present varying levels of social or socio-economic vulnerability. To ensure a meaningful cross-national comparison, census data were normalized across all municipalities included in the study. As a result, the obtained Social Vulnerability Index (*SoVI*), which ranges from 0 to 5, should be interpreted in relative rather than absolute terms, as a comparison among municipalities from different countries rather than as a standalone national measure.

In light of these findings, it would be worthwhile to extend this research to country-specific risk analyses, carried out independently for each nation. Such an approach would allow for assessing how the vulnerability of neighbouring municipalities may influence that of a single country, and vice versa, offering a more detailed understanding of interdependencies across borders.

Another key aspect concerns the selection and composition of the thematic groups. These were defined based on both literature review and availability of census data. For instance, the Governance and Institutional Capacity group includes only two variables, which consequently exert greater influence on the overall score than the individual variables within larger thematic groups such as Population or Economy. A potential methodological improvement could involve assigning lower weights to thematic groups with fewer variables, ensuring a more balanced contribution among dimensions. Moreover, additional variables could be integrated in future updates, provided they are deemed relevant and supported by reliable data, to further enhance the robustness of the vulnerability assessment.

In conclusion, this analysis highlights that Albania emerges as the most socially vulnerable country overall, while the largest differences between the two weighting scenarios (S1 and S2) are observed in North Macedonia, where the introduction of country-specific weights led to more pronounced changes in the internal ranking of municipalities.

Among the thematic dimensions considered, the Health indicator stands out as the most critical driver of vulnerability across the entire cross-border region. This reflects the persistent disparities in healthcare infrastructure, service coverage, and access particularly evident in peripheral and rural areas, where limited medical resources amplify the overall vulnerability of the population.

The ranking of the three CBR countries in terms of social vulnerability changes depending on the thematic group considered. Greece is more vulnerable in *Population* and *Governance*, North Macedonia in *Economy*, while Albania shows the highest vulnerability in the remaining groups such as *Infrastructure*, *Habitat*, and *Education*.

These findings demonstrate that national data structures and indicator relevance significantly influence the sensitivity of the Social Vulnerability Index, particularly in regions where socio-economic conditions vary sharply across short distances.

Beyond the numerical results, the analysis confirms the importance of adopting a harmonized cross-border perspective. Municipalities located along national borders, though exposed to similar environmental and seismic hazards, display markedly different levels of social and institutional capacity. This underlines the necessity of coordinated regional strategies for disaster risk reduction, since vulnerability does not stop at administrative boundaries.

Disclaimer

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