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Overview of the seismic vulnerability problem of the urban settlements in Romania

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Abstract. Seismic vulnerability is of particular interest to the scientific community, authorities and general population in Romania, given the fact that the territory of the country is mainly subject to strong intermediate-depth earthquakes that originate in the Vrancea Seismogenic Zone. However, little has been done to strengthen the resilience of urban settlements, which are especially vulnerable to earthquakes. This paper represents a summary of the seismic vulnerability problem in Romania that focuses on its various sources and on the scientific works elaborated on this topic. Also, several proposals that target both future earthquake vulnerability research and modelling actions are presented, in the endeavour to stress out the necessity of using scientific findings as grounds for decision-making.

Keywords: *vulnerability, seismic vulnerability, vulnerability assessment, Romania*

INTRODUCTION

Vulnerability is a multifaceted, protean concept that covers a wide range of definitions (Cutter 1996), referring to one common point: the propensity to register loss and damage as a result of natural or anthropogenic hazards (Coburn et al. 1994). The lack of a standard definition may be traced back to the integration of vulnerability into various scientific fields and to its scale-dependent character (Hufschmidt 2011, Izquierdo-Horna and Yepez 2022). The variety of vulnerability definitions may be regarded as a source of detrimental research fragmentation (Hufschmidt 2011) and meaning-related discrepancies (Cutter 1996) or, on the contrary, as a proof of research vitality (Adger 2006).

According to the official definition provided by UNDRR (2017), vulnerability represents "The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards.". This underlines the multidimensionality of vulnerability, corresponding to the last stage in the evolution of the concept described by Birkmann (2013).

In the last few decades, the concept has been placed more and more often at the core of risk reduction strategies, as it represents the one element in the equation of risk that may be generally modelled. The development of vulnerability into a valuable research topic is proved by the large number of literature reviews (Cutter 1996, Adger 2006, Villagrán De León 2006, Fuchs et al. 2011, Hufschmidt 2011) and also by the fact that more than a half of the global targets mentioned by the Sendai Framework for Disaster Risk Reduction (2015-2030) concern the vulnerability of human communities (UNDRR 2015).

Vulnerability should to be studied in relation to certain hazards or in a multi-hazard context, due to the fact that its particularities are strongly linked to the ones of the hazard. What is the extent of the link between the two components of risk is a matter of debate, as some scientists consider that vulnerability and hazard magnitude are independent elements; vulnerability being dependent on the physical, social, and cultural context in which the destructive event occurs (Rashed and Weeks 2003, Albulescu 2021), while others argue that vulnerability is directly influenced by the magnitude of an earthquake (Dwyer et al. 2004, Hufschmidt 2011, Armaș 2012). This division springs from the variety of vulnerability and risk definitions, and it is important to clarify and to properly operate with the two notions: vulnerability represents an underlying condition that refers to the susceptibility of being harmed (Coburn et al. 1994, Rashed and Weeks 2003, Barbat et al. 2010), while risk is defined as the degree of potential loss and damage that may be caused by all levels of hazard severity (Coburn et al. 1994); that is the product of vulnerability and hazard (Rashed and Weeks 2003, Birkmann 2013). Other debatable aspects refer to the relations between vulnerability, exposure, and resilience (Birkmann 2013).

As earthquakes are one of the most destructive natural forces on the planet, seismic vulnerability reduction is of utmost importance when it comes to the development (and even survival) of the human communities that live in earthquake prone areas, especially in the case of developing countries. Representing complex and fragile systems that function as economic growth poles, urban settlements are particularly vulnerable to earthquakes; a propensity which has been augmented by the increase in exposure associated with urban growth. This stresses out the necessities to evaluate the models that describe the interactions of the physical and social urban environments under seismic impact, and to visualise urban vulnerability (Armaș et al. 2017b).

This paper aims to present the problematic situation of the seismic vulnerability specific to the urban settlements in Romania, highlighting its sources and the contribution of the scientific community to its understanding and reduction. The overview provides a basis for the outlining of several proposals regarding future vulnerability related research and modelling actions.

SEISMIC VULNERABILITY IN ROMANIA

Romania is mainly subject to intermediate-depth earthquakes originating in the Vrancea Seismogenic Zone, being one of the European countries with the greatest seismic hazard (Vacareanu et al. 2013, Toma-Danila et al. 2018). Several seismogenic areas lie on the territory of Romania or in proximity (Figure 1): the Vrancea Seismogenic Zone, Predobrogean Depression, Făgăraș-Câmpulung Seismogenic Zone, Danubian Seismogenic Zone etc. The earthquake nest of the Vrancea Zone (Radulian 2014) is considered the most threatening both in terms of earthquake magnitude and extension of the potentially affected area: it was estimated that 2-3 major seismic events may occur per century, and that 2/3 of the country's territory is subject to subcrustal earthquakes (Vacareanu et al. 2013). The destructive force of the intermediate-depth Vrancea earthquakes was proven by the events of 1802 (7.9 MW), 1940 (7.6-7.7 MW) and 1977 (7.4-7.5 MW); that determined considerable human loss and damage (Oncescu et al. 2000, Georgescu and Pomonis 2008, 2012).

The situation of the seismic vulnerability in Romania may be considered a true predicament, as the World Bank (2020) reports. The analysis of the legislation and the technical regulations that should reduce seismic risk in this country identifies certain points that contribute to the problem, which may be summarised as follows:

- A lack of correlation between i) the legislative framework and the technical regulations that coordinate construction practices, and ii) the urbanism plans and the territorial planning strategies.
- The misuse of terminology (confusion regarding the seismic risk and seismic hazard).
- The inefficiency and ambiguity of O.G. 20/1994, the legislative document that should have coordinated the identification, evaluation and retrofitting of degraded, at-risk buildings. Failures of the current national retrofitting programme, the social and cultural factors that contributed to them, and possible solutions are thoroughly presented by Luca et al. (2016).
- The out-of-date technical assessments that should support retrofitting proposals, but that do not include budget related aspects or other practical plans. The validity of such assessments is hard to prove, and it is often contested in court in the endeavour to obtain results that would facilitate the access to funds that support energy efficiency improvements.

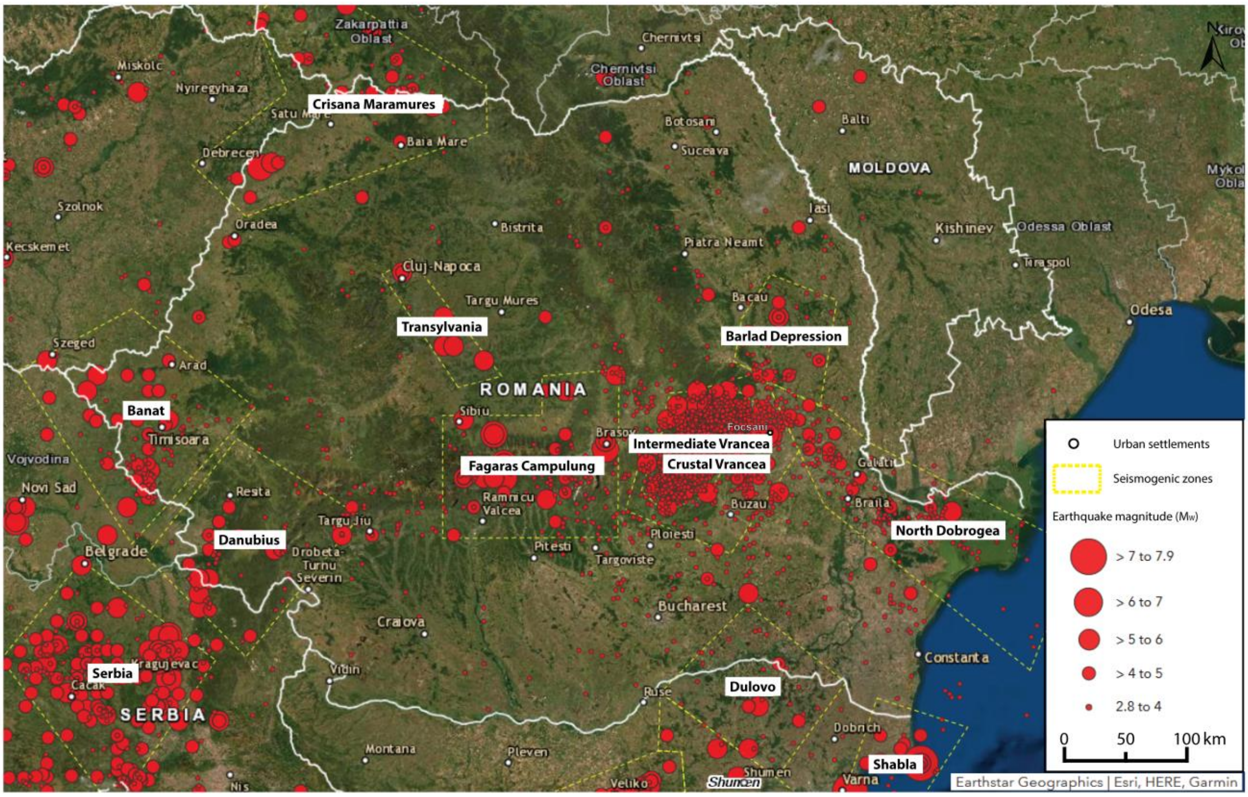

Figura 1. The seismogenic zones within or in proximity of Romania, and the locations of the BIGSEES Earthquake Catalog 2022

- Difficulties in monitoring the progress of the retrofitting process, combined with the lack of updated, comprehensive and organised data concerning the buildings that were assigned seismic risk classes (World Bank 2020).

It may be asserted that the main sources of the seismic vulnerability in Romania are of physical, geotechnical and administrative nature, but it is important to bring to attention the social ones too: the concentration of vulnerable population (i.e., the elders, unemployed or low-income individuals) in certain urban areas, the increase in exposure associated with socio-economic progress, the scarcity of educational/informative programmes concerning earthquakes, protective and preventive actions etc. Additional vulnerability sources may be included in the equation, when we take into account the various effects of the Covid-19 pandemic: health problems, increased pressure on medical services, instability of employment, changes regarding on-site/online work patterns that determine where do people spend a large part of working days, social tensions, chronic stress, etc.

The high-seismicity area located at the bending of the Carpathian Mountains, together with the aforementioned vulnerability sources, transform the reduction of seismic risk into a matter of acquiring national security. This calls for extensive research efforts oriented towards the understanding, assessment, visualisation and modelling of earthquake vulnerability, but also for proper use of scientific findings, which may be obtained only with the genuine implication of the political and economic stakeholders, emergency services and individuals.

RESEARCH OF SEISMIC VULNERABILITY IN ROMANIA

Research on seismic vulnerability is essential for the elaboration and implementation of vulnerability reduction strategies, as it aims to provide accurate answers to fundamental questions: Who/what is vulnerable and to what extent? What contributes to this level of vulnerability and to what extent? How did the vulnerability and its sources evolve over time? What can be done to reduce vulnerability, and what are the financial and time costs?

The diversity of vulnerability definitions has been fuelling the development of a multitude of assessment methodologies (Izquierdo-Horna and Yepez 2022), each with its own strengths and limitations, that fit specific purposes. Moreover, vulnerability represents an ill-structured problem (Rashed and Weeks 2003), meaning that there are many possible solutions and no ways to identify an objective optimal solution. These are only a few arguments that testify to the difficulty of operationalising the concept of vulnerability. Seismic vulnerability, as any other type of vulnerability, may not bet directly measured, but indirectly analysed (Villagrán de Léon 2006) through proxies of the physical, social and cultural contexts. Thus, the accuracy of vulnerability assessments is conditioned by the quality and quantity of the integrated datasets, as they are based on data-driven methodologies

At the beginning of the century, Calvi et al. (2006) identified two types of methodologies: i) the empirical methods (e.g., damage probability matrices, Vulnerability Index Method, continuous vulnerability curves, screening methods) and ii) analytical/mechanical methods (e.g., analytically-derived vulnerability curves, analytically-derived damage probability matrices, hybrid methods, collapse mechanism-based methods, capacity spectrum-based methods, fully displacement-based methods). It is obvious that all of them address the structural vulnerability of buildings; which emphasises the early tendency to study seismic vulnerability only relating to its physical dimension and to overlook its social, economic, systemic, institutional or political components (Birkmann 2013). This one-dimensional focus of vulnerability studies leads to biased perspectives and to "partial solutions" (Izquierdo-Horna and Yepez 2022). In time, seismic vulnerability assessments grew to encompass the aforementioned dimensions – that form what is called "comprehensive seismic vulnerability" (Barbat et al. 2010), and to be performed via new methodologies, among which multi-criteria, GIS-based methodologies and Principal Component Analysis (PCA) are the most common (Izquierdo-Horna and Yepez 2022).

Studying the scientific works that focus on the triad related to earthquakes (seismic risk, hazard and vulnerability), it appears that the vulnerability component has been explored the least in the Romanian scientific literature. This section refers only to case studies of urban settlements in Romania, because research on the seismic risk or vulnerability of rural areas has not been elaborated yet. Vulnerability represents a dynamic, multi-scalar concept, and its evaluation needs to be adapted to the scale of analysis. The methodologies used to assess the vulnerability of particular elements (e.g., buildings, individuals, groups) differ from the ones that aim to estimate the vulnerability level of cities or of their component urban areas (Tables 1, 2).

Usually, seismic vulnerability assessments of certain elements focus on a single type of vulnerability – the "building-by-building assessment" in the case of physical vulnerability, but the methodologies used to identify spatial clusters and the multi-criteria ones take into account more than one side of the concept (Table 1). The former may be considered a very technical, pioneering approach of seismic vulnerability evaluations, which determines vulnerability curves for the buildings in question (Calvi et al. 2006). Also, there are index-based methodologies that aim to estimate the physical vulnerability of the analysed buildings (Apostol et al. 2019, Mosoarca et al. 2019). In the Romanian scientific literature, the "building-by-building" approach has been used to evaluate the physical vulnerability to earthquakes of several buildings in the historic areas of Bucharest City (Vacareanu et al. 2004, Georgescu et al. 2014 are only a few of the scientists that developed this type of evaluations), Timișoara City (Roverato 2015, Valotto 2015, Taffarel et al. 2016, Chieffo et al. 2018, Apostol et al. 2019, Mosoarca et al. 2019) and Iași City (Atanasiu et al. 2008, Toma and Atanasiu 2010).

There are only a few scientific works that address the spatial clusters of high seismic risk buildings (Leon and Atanasiu 2006, Bănică et al. 2016) or that assess the seismic vulnerability of certain building types dealing with more than the structural aspects (Albulescu et al. 2019, 2020). These studies focus on Moldavian urban centres: Iași, Vaslui and Galați Cities (Table 1). It should be highlighted that the international scientific literature provides many examples of evaluations regarding the seismic vulnerability of basic facilities (the educational and health ones) – like the Sendai Framework for Disaster Risk Reduction 2015-2030 recommends, but the autochthonous literature includes only one paper on the topic (Albulescu et al. 2020).

Referring to the evaluation of seismic vulnerability at urban scale, three main approaches may be identified: one of them targets structural vulnerability (the deterministic approach), while the other two treat seismic vulnerability as a many-sided concept (the semi-quantitative and the comparative semi-quantitative assessments) (Table 2). The deterministic approach consists in damage estimations that rely on vulnerability curves (Trendafiloski et al. 2009, Lang et al. 2009), whereas the semi-quantitative vulnerability assessments are more complex, because they integrate more than one dimension of the seismic vulnerability. These are expressed using a multitude of indicators (Izquierdo-Horna and Yepez 2022) that simultaneously fulfil the conditions of relevance and data availability. The approach may be implemented focusing on a single urban centre – in the endeavour to identify its most vulnerable urban areas (Armaș 2012, Armaș et al. 2016a, Bănică et al. 2017), or on several cities, in order to determine which is the most vulnerable and what leads to this situation (Albulescu 2021). The comparative semi-quantitative approach of vulnerability assessments is an emergent one, which must be improved and performed in combination with semi-quantitative assessments of each urban settlement included in the analysis, in order to obtain salient results.

Multi-Criteria Decision-Making (MCDM) methods – more in their classical versions than in the fuzzy ones, are frequently applied to weigh the indexes and/or indices that operate as proxies of physical, social, economic, systemic vulnerability; the Analytic Hierarchy Process (AHP) being the most frequently used method (Armaș 2012, Armaș et al. 2016a, b, Armaș et al. 2017b, Bănică et al. 2017, Albulescu 2021). Also, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Weighted Product Model (WPM) have been implemented to evaluate and rank the alternatives (i.e., the cities included in comparative semi-quantitative assessments) in relation to the criteria and sub-criteria that converge to form the overall seismic vulnerability (Albulescu 2021). In some cases, MCDM methods were combined with analytical methods (e.g., the Improved Displacement Coefficient Method) that create custom-defined vulnerability functions used for building damage estimation, leading to more robust frameworks (Armaș et al. 2016b, Armaș et al. 2017b).

Tables 1 and 2 pinpoint the spatial disparities of the scientific works on seismic vulnerability in Romania. Most of these articles analyse the seismic vulnerability of Bucharest, which is the EU capital with the greatest earthquake risk (Armaș et al. 2016a, 2017b) – partly determined by the great seismic hazard associated with the Vrancea Seismogenic Zone, partly by the ongoing degradation of its building stock (Armaș et al. 2017b). Besides the most populous city of Romania, other urban settlements that have been studied in terms of seismic vulnerability are Timișoara, Iași, Vaslui, Galați and Focșani Cities.

“VULNERABILITIES” OF THE SCIENTIFIC RESEARCH

The literature review on the seismic vulnerability of urban settlements in Romania shows that the topic has drawn more and more scholarly interest since the beginning of the century, and that the last decade brought momentous scientific progress. However, all the cited references, regardless of their approach, present one major objective drawback: the integration of out-of-date population and building stock datasets. Some scientific articles rely on data provided by the Population and Housing Census of 2002 (Trendafiloski et al. 2009, Armaș 2012, Armaș and Gavriș 2013, Armaș 2016a, b) or 2011 (Armaș et al. 2016a, 2017b, Albulescu 2021), which do not properly illustrate today’s reality. The integration of updated data, part of which can be obtained via remote sensing and GIS processing, would increase the accuracy of the seismic vulnerability assessments.

PROPOSALS CONCERNING SEISMIC VULNERABILITY RESEARCH AND MODELLING

The overview of the sources that contribute to the seismic vulnerability of the urban settlements in

Romania and the study of the existing scientific literature elaborated on this topic point out the bottlenecks that hinder the implementation of vulnerability reduction vulnerability reduction plans. To address the issue, several proposals concerning seismic vulnerability modelling may be set up. These can be divided in actions that directly reduce seismic vulnerability and proposals referring to research, that supports and coordinates ameliorative actions.

The former category includes the following proposals:

- To update the technical assessments of old buildings (especially the ones that were affected by the 1940 and/or the 1977 earthquakes).
- To modify the legislative framework and the associated technical regulations in order to facilitate the retrofitting/demolition process of high-risk buildings (Luca et al. 2016).
- To modify the legislative framework that coordinates the construction of buildings in areas with geological settings that are subject to liquefaction/landslides, aiming to ensure that the new buildings can withstand powerful seismic shocks.
- To develop near real-time software that run emergency intervention scenarios based on the near real-time seismic damage estimation programme (i.e., SEISDARO) developed by Toma-Danila et al. (2018).
- To develop educational programmes regarding earthquakes, seismic adjustments, preventive and protective behaviour. These should target not only pupils and students, but also the active population and the elders.

The proposals concerning the enhancement of vulnerability related research are:

- To provide the scientific community with updated, reliable, spatial and statistical data regarding the technically assessed buildings, the number and characteristics of their residents. The integration of these datasets into vulnerability assessments would translate into a leap of progress that would properly support decision-making. Also, the public should be granted access to data concerning the building stock, so that one can make informed decisions about their residence.
- To improve the accuracy of Population and Housing Census data and to create spatial datasets that correspond to the statistical ones. This would enhance the reliability of social vulnerability assessments.
- To identify the institutional and political sources of vulnerability (preferably at local scale) and to integrate them into seismic vulnerability assessments.
- To perform Sensitivity Analyses or other validation methodologies that can support the reliability of the results, given the inherent uncertainties that appear in vulnerability assessments.
- To use the findings of seismic risk perception studies (Armaș and Avram 2008, Armaș et al. 2017a, Albulescu et al. 2021, Ionescu et al. 2021) as proxies of individual vulnerability, focusing on psychological aspects and seismic adjustment implementation at household scale.
- To increase the use of GIS techniques in the visualisation of urban vulnerability (Toma-Danila et al. 2017). Moreover, remote sensing may be used to acquire up-to-date building stock data.
- To continue to perform seismic vulnerability assessments at local scale, targeting the identification of the most vulnerable neighbourhoods and human communities, and to use these findings as a basis for urgent vulnerability modelling actions.
- To perform comparative multi-criteria seismic vulnerability assessment at county and regional level in order to identify the most vulnerable urban settlements, to prioritise seismic risk reduction-oriented funds, and to plan in advance the terminal points of the potential flux of human and material resources that may be needed to reduce the seismic impact of a future major earthquake.
- To use the scientific studies on seismic vulnerability as a cornerstone for emergency management plans, including the red intervention plans that ought to be implemented in the aftermath of a major earthquake.

CONCLUSIONS

Vulnerability is an underlying ever-changing condition of human communities and their assets, which must be assessed at different scales and moments, considering distinct dimensions, if the society wants to model it towards acceptable levels. Ultimately, it may be asserted that the effectiveness of vulnerability assessments and modelling actions dictate the development of the communities in question. The overview of the urban seismic vulnerability in Romania brings to light the gap between the progress of the scientific work – which provides results that may bolster seismic vulnerability reduction, and the actual actions that are implemented to reach this goal. This implies that authorities, emergency services and stakeholders should integrate practical knowledge on seismic vulnerability into legislative frameworks, technical regulations and local scale seismic risk reduction plans, using scientific findings as grounds for decision-making.

Table 3. Vulnerability assessments of certain elements in urban settlements

Approach	**Methods**	**References**	**Study area/Assessed elements**
Building by building assessment	Out of plane local mechanisms of collapse	Roverato (2015)	Timișoara City (Cetate and Iosefin areas)
		Taffarel et al. (2016)	Timișoara City (Historical Centre and Iosefin areas)
	In plane and in plane mechanisms of collapse	Valotto (2015)	
	EMS-98-based physical vulnerability assessment	Chieffo et al. (2018)	Timișoara City (Unirii Square)
	Vulnerability Index Method, Nonlinear seismic analysis	Apostol et al. (2019)	Timișoara City (Fabric historic area)
	Vulnerability Index Method, Vulnerability Index Method modified to include the cultural value of the buildings	Mosoarca et al. (2019)	Timișoara City (Fabric and Iosefin historic areas)
	Artificial intelligence and GIS-based non-linear analysis	Atanasiu et al. (2008)	Pilot study on several damaged buildings in Iași City
	Deterministic approach, Finite Element Model Description	Toma and Atanasiu (2010)	P+4 residential buildings in Iași City
	HAZUS and ATC-40 methodologies, Monte Carlo simulations	Vacareanu et al. (2004)	Pantelimon Building (Bucharest)
	Mean Damage Degree method	Georgescu et al. (2014)	Bucharest (Civic Centre)
Spatial cluster identification	Supervised clustering based on the k-nearest neighbour graph method	Leon and Atanasiu (2006)	Pilot study on several damaged buildings in Iași City
	Cluster analysis, Principal Component Analysis of the buildings that were assigned seismic risk classes	Bănică et al. (2016)	Iași City
Semi-quantitative vulnerability assessment	Multi-criteria assessment of the buildings that were assigned seismic risk classes (based on Fuzzy AHP and TOPSIS)	Albulescu et al. (2019)	Galați City
	Multi-criteria assessment of school units (based on AHP and WPM)	Albulescu et al. (2020)	Vaslui City

Table 4. Vulnerability assessments of urban settlements

Approach	Methods	References	Study area
Deterministic damage and loss assessment	Loss estimation model based on building stock vulnerability curves and soil conditions	Trendafiloski et al. (2009)	Bucharest
	Damage and loss estimation model based on building stock vulnerability curves	Lang et al. (2012)	
Semi-quantitative vulnerability assessment and Index construction	Multi-criteria analysis of social vulnerability (based on AHP): Social Vulnerability Index	Armaș et al. (2016b)	
	Improved Displacement Coefficient Method, custom-defined vulnerability functions: building damage estimation	Armaș et al. (2017b)	
Semi-quantitative vulnerability assessment	Multi-criteria methods: - Social Vulnerability Index (SoVI model) - Spatial multi-criteria Social Vulnerability Index (SEVI model)	Armaș and Gavriș (2013)	
	Spatial multi-criteria analysis (based on AHP)	Armaș (2012)	
		Armaș et al. (2016a)	
		Bănică et al. (2017)	Iași City
Comparative semi-quantitative vulnerability assessment	Comparative multi-criteria assessment of 4 urban centres in Moldavia Region (based on AHP, Fuzzy AHP, TOPSIS and WPM)	Albulescu (2021)	Iași, Vaslui, Galați, Focșani Cities

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