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Open Source Data-Based Solutions for Identifying Patterns of Urban Earthquake Systemic Vulnerability in High-Seismicity Areas

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Abstract: Urban settlements located in high-seismicity areas should benefit from comprehensive vulnerability analyses, which are essential for the proper implementation of vulnerability modelling actions. Alas, many developing countries face a shortage of knowledge on seismic vulnerability, particularly concerning its systemic component, as a consequence of a combination of data scarcity and a lack of interest from authorities. This paper aims to identify primary time-independent spatial patterns of earthquake systemic vulnerability based on the accessibility of key emergency management facilities (e.g., medical units, fire stations), focusing on the urban settlements located in the high-seismicity area nearby the Vrancea Seismogenic Zone in Romania. The proposed methodological framework relies on open source data extracted from OpenStreetMap, which are processed via GIS techniques and tools (i.e., Network Analyst, Weighted Overlay Analysis), to compute the service areas of emergency management centres, and to map earthquake systemic vulnerability levels. The analysis shows that accessibility and systemic vulnerability patterns are significantly impacted by a synergy of factors deeply rooted in the urban spatial layout. Although the overall accessibility was estimated to be medium-high, and the overall systemic vulnerability to be low-medium, higher systemic vulnerability levels in certain cities (e.g., Bacău, Onești, Tecuci, Urziceni). The presented findings have multi-scalar utility: they aid in the development of improved, locally tailored seismic vulnerability reduction plans, as well as the allocation of financial and human resources required to manage earthquake-induced crises at regional scale. Further to that, the paper provides a transparent methodological framework that can be replicated to put cities in high-seismicity areas on the map of systemic vulnerability assessments, laying the groundwork for positive change in countries where the challenges associated with high-level seismic risk are often overlooked.

Keywords: earthquake vulnerability; systemic vulnerability; urban seismic vulnerability; emergency management; spatial patterns

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1. Introduction

The first hours of a natural-hazard-induced crises are crucial for the survival of victims and the limitation of damage. The pressure of the narrow timeframe calls for immediate and effective emergency interventions that aim to find and save injured people [1] and also prevent the manifestation of other cascading hazards or to limit their effects [2]. In practice, multiple objective and subjective factors hinder prompt and efficient interventions, leading to delayed results [1] or, in a worst-case scenario, to negative outcomes that could have been avoided altogether. These predicaments are usually associated with very powerful hazardous events with rapid manifestation (i.e., earthquakes, hurricanes, floods, etc.), which cause great disruption and delay the implementation of emergency management plans.

Earthquakes rank at the top of such impactful natural hazards, partly due to the fact that their prediction is more difficult than the forecasting of climatic or hydrological hazards [3,4]. A handful of common consequences of major earthquakes, i.e., people buried under collapsed buildings [5–7], widespread panic-induced behaviours [8,9], streets blocked by building debris and other transport infrastructure failures [10], earthquake-induced fires [11,12], earthquake-triggered landslides and other slope failures [13–15], or even tsunamis [16–18], is enough to paint a disturbing aftermath picture. Such effects are hard to manage in an efficient way, even without the inherent time pressure, especially in developing countries [19] and in the post-COVID-19 era [20,21].

Nevertheless, sound earthquake risk mitigation plans that are tailored to local socio-economic realities and their subsequent adequate implementation help attenuate the impact of major earthquakes. The elaboration of optimal strategies requires knowledge about the location, accessibility, and capacity of key post-seism emergency facilities (i.e., medical units and fire stations) that are in charge of managing earthquake-induced crises. These aspects relate to systemic vulnerability, which is the facet of seismic vulnerability that can be modelled at the lowest cost of both time and money. Systemic vulnerability is rarely defined in a consistent way, but potential weaknesses of emergency management (in terms of infrastructure capacity and failures of functionality, accessibility to hospitals and fire) [22–29] and failures of transport network functionality [30–35] are common themes. By adapting the United Nations Office for Disaster Risk Reduction (UNDRR) [36] definition of vulnerability, its systemic component can be conceptualised as the emergency management-related "factors and processes which increase the susceptibility of an individual, a community, assets or systems to the impact of hazards."

Cities are human settlements with significant population densities that are bound to increase their exposure through economic development [37–39]. Understanding the systemic vulnerability of urban areas is the key to ensuring their safety, especially if they are located in high-seismicity areas. Unfortunately, in many developing countries, these matters are ignored due to a plethora of factors (i.e., insufficient financial resources, lack of interest from authorities and the civil society). Romania constitutes a telling example, considering that it is subject to seismic activity originating from one of the most active seismogenic areas in Europe [40] and that different dimensions of seismic vulnerability (i.e., structural, social, economic, and systemic), although well-represented in many of its urban settlements, are not sufficiently studied [41].

Despite the fact that the seismic hazard specific to the Vrancea Zone has been studied since the end of the 19th century [42], research works focusing on the earthquake vulnerability of the nearby settlements are of very recent date [28,43]. Research on seismic vulnerability in Romania dates back to 2004 [44] and gained momentum in the second decade of this century [24,45,46], but it has only focused on the capital of the country, leaving behind provincial cities [41]. Scaling down to the systemic component of urban seismic vulnerability, few studies integrate it among other vulnerability dimensions [24,43], and even fewer focus on this particular facet [24,34,35,47].

This paper aims to identify spatial patterns of earthquake systemic vulnerability in a high-seismicity area located in Romania, based on the accessibility of emergency management facilities with key responsibilities in a post-seismic context (e.g., search and rescue operations, limitation of cascading hazards). By taking under analysis precisely the cities that need such assessments the most, this study represents a big step forward in filling the research gap concerning seismic systemic vulnerability, also providing valuable results that assist in the outlining of post-seismic emergency management strategies, allowing for more efficient and timely interventions. Another contribution of the paper consists of putting forward a replicable solution to the problem of scarce, obsolete, or incomplete data that need to be integrated into earthquake vulnerability assessments: a methodological framework that relies upon open source datasets that can be handily collected and processed to identify primary time-independent systemic vulnerability patterns.

The paper starts with an overview of the high-seismicity study area and the selected urban settlements and continues with a description of the proposed methodological framework. This is followed by the Results section, which details the accessibility and systemic vulnerability patterns. The findings are interpreted and placed into context, and the scientific contributions of the paper, together with its limitations, are discussed.

2. Study Area

The selection of the study area was based on the parameters that indicate significant levels of seismic hazard, in this case, a 0.35 g threshold of peak ground acceleration (PGA), which is computed for a 225-year average recurrence interval with an exceedance probability of 20% in 50 years [48]. The study area includes the source of the seismic activity: the Vrancea Seismogenic Zone, which is located SE of the Carpathian Arch (Figure 1). This earthquake nest [49] presents foci of 60–200 km depth [50], being the only one in Romania with a subcrustal domain [51]. The intermediate depth seismicity may affect two-thirds of Romania's territory, along with the ones of neighbouring countries [52]. Noteworthy major earthquakes originating in this seismogenic zone were recorded in 1802 (7.9 M_W), 1940 (7.6–7.7 M_W), and 1977 (7.4–7.5 M_W) [53–56].

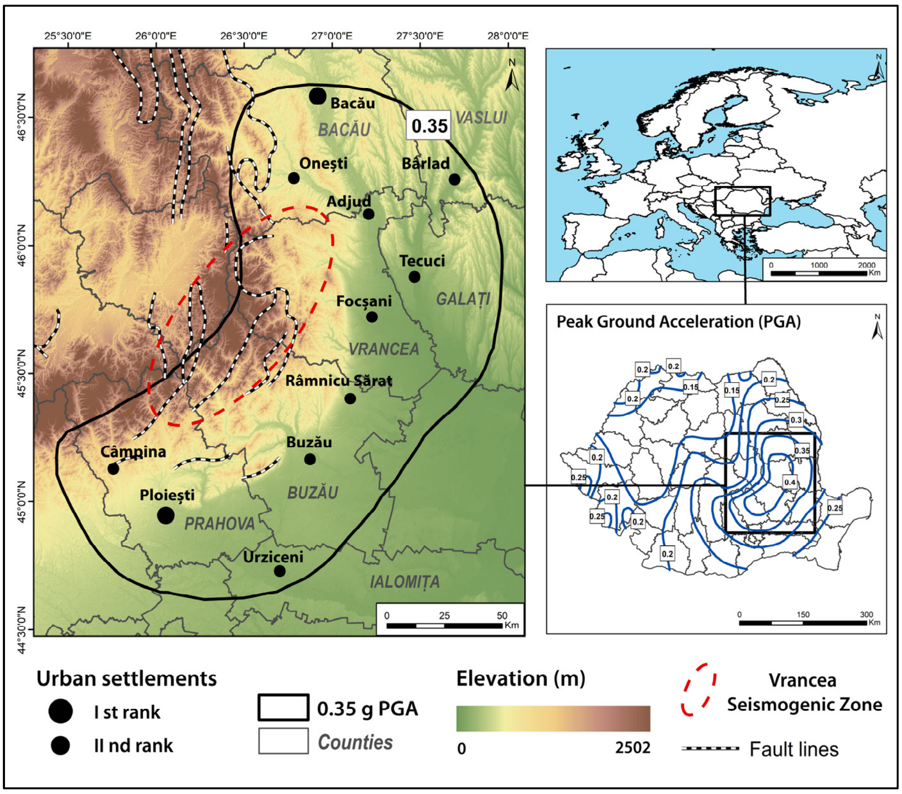

Figure 1. Location of the high-seismicity study area and of the selected urban settlements (Data source used for mapping: [48,57,58]).

The study area extends over 10 counties, but its coverage is prominent only in five of them (i.e., Bacău, Galați, Vrancea, Buzău, and Prahova counties) (Figure 1). There are 32 urban settlements located within this area, of which 11 were selected based on their high-level demographic size, administrative role, economic profile, and influence (Table 1). These are divided as follows:

- I[st] rank cities (i.e., Ploiești and Bacău): over 150 thousand inhabitants that have access to the pan-European transport network, benefit from a complex economic profile and high-end medical and education services, and with regional influence areas [59].

- IInd rank towns: 10–150 thousand inhabitants, which are less connected to the pan-European transport network, display more basic economic profiles, have fewer health-care and education facilities, and have county- or local-scale influence areas [59]).

Table 1. Details regarding the selected urban settlements in the high-seismicity area (Data sources: [48,59,60].

Urban Settlement	County	PGA (g)	Population	Economic Profile	Importance Rank
Bacău	Bacău County	0.35	194,004	Complex economic profile, administrative function	I
Onești		0.35	48,732	Industry-based economic profile	II
Ploiești	Prahova County	0.35	216,134	Complex economic profile, administrative function	I
Câmpina		0.35	34,954	Industry-based economic profile	II
Focșani	Vrancea County	0.40	88,933	Complex economic profile, administrative function	
Adjud		0.40	19,553	Industry and service-based economic profile	
Buzău	Buzău County	0.35	126,144	Complex economic profile, administrative function	
Râmnicu Sărat		0.35	38,109	Industry and service-based economic profile	
Bârlad	Vaslui County	0.35	67,112	Industry and service-based economic profile	
Tecuci	Galați County	0.35	48,109	Industry and service-based economic profile	
Urziceni	Ialomița County	0.35	15,998	Industry-based economic profile	

Due to their proximity to the epicentres of major earthquakes, but also the local vulnerability conditions mainly related to old building stocks, these urban settlements were severely affected by the major earthquakes of the past century. The study area corresponds to VIII–X intensity levels on the re-evaluated macroseismic map of the 1940 earthquake [55], and to VII–X intensity levels on the re-evaluated macroseismic map of the 1977 earthquake [56]. The 1940 earthquake caused both human deaths and injuries in Focșani, Bârlad, Tecuci, Câmpina, and Ploiești [54], and all of the counties listed in Table 1 were mentioned among the ones with significant proportions of buildings that were affected/destroyed by the 1977 earthquake, or that needed strengthening/repairing after this hazardous event [61]. Considering the impact of past major seismic events, together with the causes of such high-level damage, it becomes clear that further research on seismic vulnerability is motivated by practical reasons related to safety and wellbeing.

3. Methodology

3.1. Vulnerability Operationalisation Approach

The pluralism of interpretations supported by the systemic dimension of earthquake vulnerability allows for a wide range of operationalisation approaches, each with its own strengths and limitations. The accessibility [24–26,28,62–64], capacity [23,28], and functionality [22] of emergency management services can have augmenting or attenuating effects on the level of systemic vulnerability, which makes them relevant for its assessment. These aspects may be corroborated by the serviceability of transportation routes [22,23,32,34,35,47,65] for more comprehensive earthquake scenario-based assessments.

In this paper, systemic vulnerability was operationalised based on the accessibility of key emergency management centres (i.e., medical units and fire stations) in the context of a major earthquake (of at least 7 M_W). Accessibility refers to the ease of reaching a certain point starting from a given location [66], and it may be measured in physical distance or as the time required to travel this distance. Time-dependent assessments rely on particular post-earthquake scenarios defined by month, week, and time of day, which in turn require specific traffic datasets. Since such datasets are not readily available in most developing countries, including Romania, the distance-based assessment option was chosen. Therefore, the methodological framework does not refer to a particular post-earthquake scenario but rather aims to present a spatial overview of the earthquake systemic vulnerability levels specific to the Romanian urban settlements in the proximity of the Vrancea Seismogenic Zone.

3.2. Data Collection and Processing

The spatial analysis was performed following the methodological workflow illustrated in Figure 2, and it required data concerning the location of emergency management facilities, the spatial configuration of the urban street network, and the limit of the urban built-up area (Table 2). In order to ensure the reproducibility of the methodological framework, open source datasets were integrated.

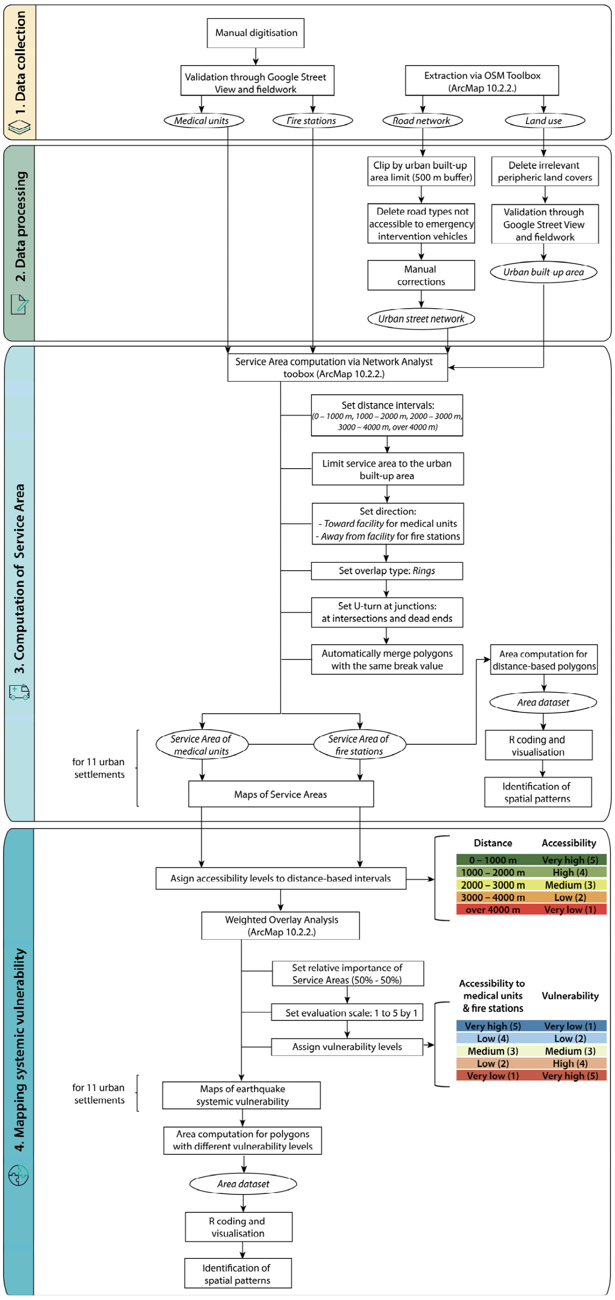

Figure 2. Methodological framework consisting of 4 steps: 1. Data collection; 2. Data processing; 3. Computation of Service Areas; 4. Mapping systemic vulnerability.

Table 2. Dataset details and sources.

Dataset	Source	Data Collection/Processing Observations
Medical units	Manual digitisation over theOSM basemap [67]	The dataset included only the medical units suited to offer health assistance in the aftermath of a major earthquake. Therefore, small medical facilities and private hospitals were excluded from the spatial analysis. Additionally, medical facilities with special profiles, where the usual needs of the patients are demanding enough even in non-seismic contexts (i.e., psychiatric, pediatric, tuberculosis hospitals, and maternities), were excluded. Data validation was performed using Google Street View and through field observations.
Fire stations	Manual digitisation over the OSM basemap [67]	The dataset included all the fire stations with firefighter teams that may be called to action in the aftermath of a powerful earthquake. The tasks of these teams include both fire limitation actions and search and rescue procedures. Data validation was performed using Google Street View and through field observations.
Urban street network	OSM [67]	The dataset was extracted using the OpenStreetMap Toolbox in ArcMap 10.2.2 software. Certain highway features were deleted from the initial dataset due to the fact that they were not suitable for intervention vehicles. Manual corrections were performed in the final processing stage.
Urban built-up area limit	OSM [67]	The dataset was computed using land use data extracted via OpenStreetMap Toolbox in ArcMap 10.2.2 software. Peripheral areas with land covers that may generate low population densities or inconsistent habitation patterns were removed from the dataset. Data validation was performed using Google Street View and through field observations.

The spatial locations of the emergency service centres in each urban settlement were manually digitised, and the urban street network dataset was extracted from the OpenStreetMap (OSM) portal [67]. Another spatial dataset that needed to be integrated into the analysis is the limit of the urban built-up area for each urban centre in Table 1. The boundary was computed using the land use dataset provided by [67] and was designed to exclude large peripheral industrial units with heavy industry profiles, as well as farmlands, farmyards, forests, grasslands, orchards, and vineyards because these are defined by low population densities and inconsistent habitation patterns.

Further, in the processing stage, the urban street network was modified to better fit the scope of the spatial analysis by deleting the road types that cannot be used by emergency intervention vehicles. Therefore, the bridleway, construction, corridor, crossing, cycleway, footway, path, pedestrian, proposed, raceway, steps, and track features from the OSM highway nomenclature [68] were deleted from the attribute table of the vector. The extension of the road network specific to each urban settlement was limited to a buffer of 500 m from the boundary of the urban built-up area. In addition, we performed a manual correction of the urban street network dataset, aiming to delete the unnecessary (i.e., isolated) road segments that reach beyond the set limit or to connect proximal roads that were segmented by this limit. In the final stage of data processing, the vector was transformed into a road network file, which was integrated with the location of the key emergency facilities in order to generate service areas (Figure 2).

3.3. Computation of Service Areas

The computation of the service areas was performed in ArcMap 10.2.2. software via the Network Analyst tool (Figure 2, Section 3). This represents a proprietary GIS software extension that can be used to solve network problems, among which the identification of a service area around a specific location is one of the most useful. The Service Area extension allows for the generation of a region that includes the components of a street network located within a specified impedance (which is commonly measured in distance or travel time). The data regarding the extent of the service area were subsequently analysed using the R package collection called tidyverse [69] in RStudio software. This collection allows for the import, wrangling, and visualisation of the service area-related data.

At this step, the service areas composed of general polygons delimited by 1000 m intervals (i.e., 0–1000 m, 1000–2000 m, 2000–3000 m, 3000–4000 m, over 4000 m) were generated for the medical units and fire stations in each of the selected urban settlements. The service areas' boundaries were set to correspond to those of the urban built-up area. General polygons were selected for this analysis instead of detailed ones because of increased processing speed at the cost of a 0.1% difference in the polygons' area.

Separate protocols were applied for medical units and fire stations: the service areas of the former were computed toward the facility, while the service areas of the latter were generated away from the facility (Figure 2, Section 3). This is motivated by the fact that in a post-seismic context, medical units represent the end points of emergency interventions, whereas fire stations make up starting points.

For all service areas, the "ring" option was preferred as the overlap type of the polygons, and the trimming limit was set to 100 m. This means that the polygons of larger distances do not include the smaller ones and that polygon limits correspond to consecutive breaks. Additionally, it was assumed that emergency intervention vehicles would be able to perform U-turns at intersections and dead ends in accordance with post-earthquake traffic permissions. In the case of multiple medical units or fire stations, the distance-based polygons with the same break values were automatically merged. This option was preferred because it optimises the service area computation process since it eliminates the necessity to correct overlapping areas that would have been generated by other procedures.

This first part of the spatial analysis resulted in 11 service area maps of medical units and 11 service area maps of fire stations. Each set was analysed, looking for patterns of accessibility. In addition, the areas of the distance-based polygons were computed in ArcMap 10.2.2. R code written in RStudio was used to analyse and visualise the area dataset, optimising the identification of accessibility patterns (Figure 2, Section 3).

3.4. Mapping Systemic Vulnerability

Each distance-based interval was assigned an accessibility level, as shown in Figure 2 (Section 4). The closer a particular neighbourhood is to a medical unit or a fire station, the more reachable it is in a short time (i.e., more accessible), which is crucial in a post-seismic context. The vulnerability levels were established based on the overlap of two areas with the same accessibility level to medical units and fire stations, respecting the reversed relation between accessibility and vulnerability (Figure 2, Section 4). For example, very low vulnerability levels result from the overlapping of areas characterised by very high accessibility to both medical and fire management facilities. In other words, the areas with this vulnerability level are located less than 1000 m away from both a medical unit and a fire station.

The mapping of earthquake systemic vulnerability was performed via Weighted Overlay Analysis using the tool with the same name from ArcMap 10.2.2 software. This proprietary GIS software extension allows for the overlaying of different rasters with a common measurement scale and for weighting operations based on the rasters' relative importance. This means that the results are dependent on both evaluation scales and relative importance values. Therefore, the decisions regarding evaluation scales and weights are of primary importance and have to rely on scientific expertise and empirical knowledge. In this procedure, the values of the rasters (which have to correspond to the common measurement scale) are multiplied by the value of relative importance. Next, the resulting values are summed up and written to new cells in an output layer.

In the current application, service area vectors of medical units and fire stations in each city were converted into raster format. We considered that the accessibility of medical units was equally important as the accessibility of firefighter teams to intervention points, which translated into a 50% relative influence for the service areas of medical units and a 50% relative influence for the service areas of fire stations. The evaluation scale was set to 1 to 5 by 1, corresponding to the 5 accessibility levels (Figure 2, Section 4).

At this point, a new set of 11 maps illustrating the level of seismic systemic vulnerability was generated and analysed in terms of spatial patterns. The raster datasets were converted back to vector polygons in order to compute the areas specific to the 5 vulnerability levels for each urban settlement. The area dataset was analysed using R code and transformed into visualisations that facilitate the identification of systemic vulnerability patterns.

4. Results

This section introduces the factors that contribute to the spatial configuration and extension of service areas specific to medical units and fire stations (i.e., number of facilities, position of facilities, the shape of the built-up area, the configuration of the urban street network, and the presence of accessibility limiting elements, such as railroads or natural features) (Figure 3), continuing with the identification of accessibility patterns. Next, the results of the Weighted Overlay Analysis are presented, focusing on the identification of earthquake systemic vulnerability patterns.

Six out of the eleven urban settlements are served by only one medical unit, and almost all of them are protected from fires by only one fire station. Ploiești City benefits from the largest number of medical facilities (seven) and fire stations (two). Next on the list are Buzău, Focșani (each with three hospitals), Bacău and Onești (each with two hospitals), and one fire station (Figure 3).

The number of cities where the sole medical unit is located close to the geometric centre of the urban area (e.g., Râmnicu Sărat, Tecuci) is lower than the one where the medical unit is located in a marginal position: in the N (e.g., Bârlad), S (e.g., Adjud, Urziceni) or W (e.g., Câmpina) of the urban territory (Figure 3). In the cities that benefit from multiple medical facilities, clustering is frequent in the N (e.g., Ploiești, Focșani, Onești), E (e.g., Ploieșt), SE (e.g., Buzău) or central (e.g., Bacău) parts of the city. In addition, there are cities with medical facilities that are very close to each other (i.e., Focșani, Onești), which results in an overlap of distance-based polygons.

Fire stations hold a central or almost central position in half of the urban settlements served by only one firefighter department (i.e., Buzău, Bârlad, Focșani, Tecuci, Bacău). There are also cities where fire stations are located on the outskirts: in N (e.g., Onești), S (e.g., Râmnicu Sărat), or W (e.g., Adjud, Câmpina, Urziceni). As mentioned before, Ploiești City, which is the largest urban centre out of the 11 settlements, is served by two fire stations with central and S positions (Figure 3).

Most of the urban settlements under analysis have intricate shapes, with many peninsula-resembling features that extend to N (Bacău, Râmnicu Sărat, Tecuci), NE (Câmpina, Bacău, Bârlad), NW (Bacău, Buzău, Ploiești, Focșani, Onești), and S (Bacău, Buzău, Ploiești, Tecuci, Onești, Focșani) (Figure 3). In certain cases, such peninsular features are connected to the main urban area only by one road, which greatly reduces accessibility to emergency services centres as well as other urban facilities. Bacău City offers such an example; its NE neighbourhoods are cut off from the rest of the urban area by the Bistrița River and the reservoirs along it, which are crossed by a single road bridge. It is worth mentioning that large peripheral industrial areas that were not included within the urban built-up area determine the piercing of the urban territory by hole-resembling features, favouring the emergence of such peninsula-shaped neighbourhoods at the urban fringe. This situation is characteristic of large cities such as Ploiești and Buzău. On the other hand, Adjud and Râmnicu Sărat have the advantage of a more compact shape of the urban built-up area, which sets the stage for increased accessibility.

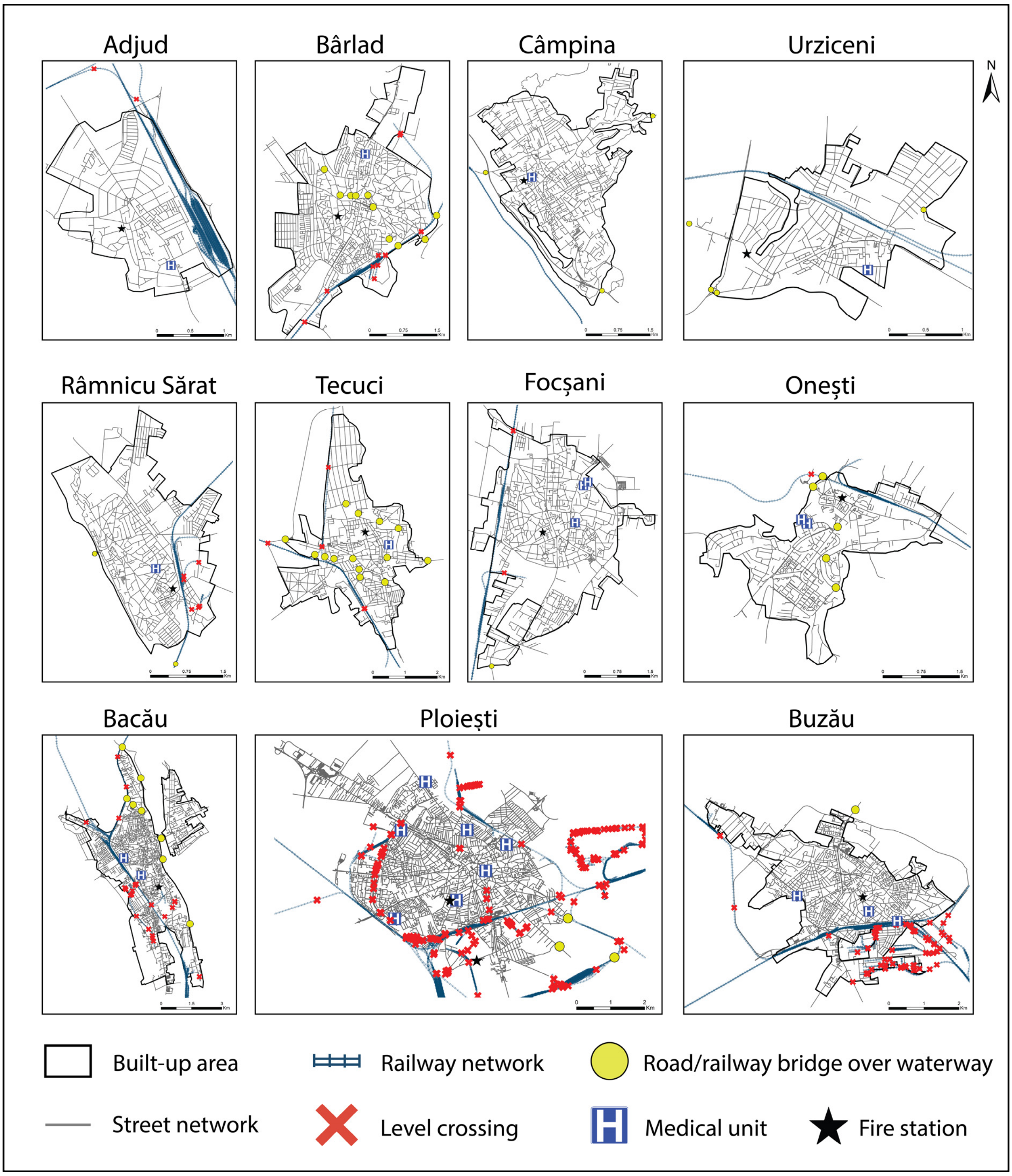

Figure 3. The location of key emergency management facilities and the spatial configuration of the urban street network, in the 11 urban settlements (Data sources: [67]) The scale was adapted for each urban settlement to better portray the urban street network.

The density and spatial configuration of the urban street network should also be taken into consideration when analysing accessibility and seismic systemic vulnerability patterns. Most of the cities located in the study area have a high street density in central neighbourhoods (e.g., Bârlad, Câmpina, Focșani, Tecuci, Râmnicu Sărat, Bacău, Ploiești, Buzău), which allows for increased accessibility levels and implicitly low vulnerability levels. Furthermore, the mix of curvilinear loops and chaotic street patterns (Figure 3) is common in central urban areas with a high population density. The density of the street network reduces toward the urban periphery in all of the cities, where recent residential areas are yet to expand in terms of road connectivity or where specific land covers (i.e., industrial areas, deposits, military/police units, parks, urban forests, or other natural areas) impose this. Several of these land covers are also found deeper into the urban territory, limiting accessibility due to fewer or less connected streets (Figure 3).

Another thing to consider is the presence of railroads, which tend to limit accessibility if not crossed by level crossings. This may also account for a road connectivity liability, most notably in the case of a level crossing obstruction with debris, which would cause impairments of both roads and railroads, cutting off access to nearby neighbourhoods located on the crossing's sides. Furthermore, the collapse of road bridges over waterways may result in significant road functionality impairment and the same limitation of accessibility in nearby neighbourhoods. Also, a railroad bridge collapse triggered by a major earthquake may have fatal consequences in case of train derailments.

4.1. Accessibility to Medical Units

The distance-based polygon coverage data to medical facilities show that most of the cities have a favourable situation in terms of accessibility to healthcare services: the most prominent accessibility level in terms of the covered area is high accessibility (1000–2000 m), and the majority of urban settlements have at least half of their territory no more than 2000 m away from the nearest medical facility (Figure 4). The numerous healthcare units in Ploiești City are mainly responsible for the very large (about 75%) urban area located within 2000 m of the nearest medical unit, while the intricate shape of Bacău City, despite the central position of its two hospitals, leads to very low and low accessibility levels for over 50% of the urban territory. In the category of small cities served by a single hospital, Râmnicu Sărat and Adjud stand out as having large areas with higher accessibility levels (over 50% of the urban area).

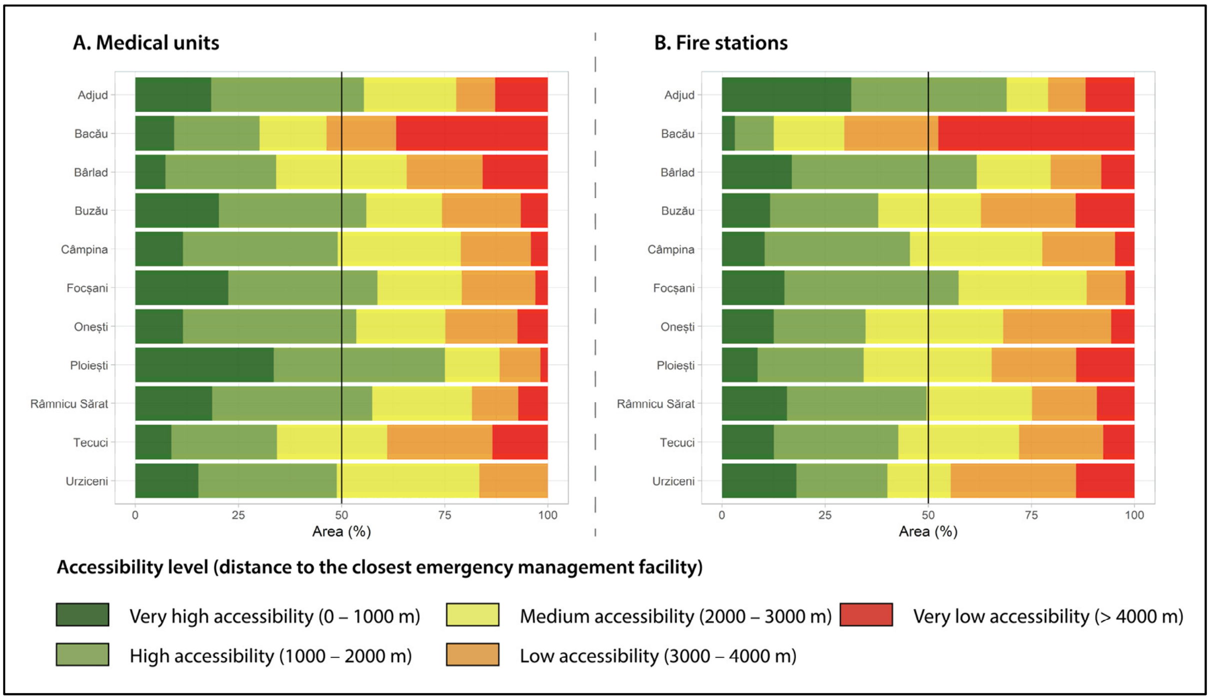

Figure 4. Areas (as percentage of urban territory) of accessibility levels and distance-based polygons to the (**A**). medical units, (**B**). fire stations, in the 11 urban settlements.

Zooming in on the maps of service areas specific to medical units (Figure 5), one may observe different spatial patterns of accessibility for cities that are served by only one health centre and for cities that have more facilities of this type. In the first case, the service area of the medical unit extends in a radial manner, in a direction that is heavily dependent on the position of the hospital. For instance, the W position of the Municipal Hospital in Câmpina City determines the extension of the service area from W to E, while the E position of the medical facility in Tecuci City sets up a service area extending from E to W. This means that the cardinal point that designates the position of the medical unit also designates the urban areas where the limits of distance-based polygons are closer to each other. In the opposite part of the urban territory, the limits of the polygons are placed at larger distances, meaning that the service area is more extended in that direction. Other patterns of opposite extension direction, determined by the marginal positions of medical facilities, may be observed in Adjud City, where the medical unit has an S position and the service area extends from S to N, and in Bârlad City, where the N position of the hospital determines a service area that extends in the opposite way. On the other hand, the central position of the medical unit in Râmnicu Sărat determines a more balanced, radial extension of the service area, meaning that the limits of the distance-based polygons tend to be equally spaced in all directions (especially in the case of urban built-up territories with compact shapes).

In cities with a single healthcare unit, green areas designating very high and high accessibility hold central positions (e.g., in Adjud, Urziceni and Câmpina, Râmnicu Sărat) and account for more than or about a half of the urban area (Figures 4 and 5). This is a consequence of the central location of medical units (e.g., Râmnicu Sărat), the compact shape of the urban territory (e.g., Râmnicu Sărat and Adjud), or the high street density in the central areas (e.g., Urziceni, Câmpina Râmnicu Sărat, and Adjud). Lower extensions of the green areas are observed in Tecuci and Bârlad (Figure 5) due to the combination of the marginal positions of medical facilities, extensive peninsular features, and areas with lower street density.

The opposite end of the accessibility spectrum is illustrated by the red and orange colours. Cities with complex-shaped territories (e.g., Tecuci, Bârlad) present larger areas located at more than 3000 m of the medical facility (over a third of the territory), which generally correspond to the peripheral neighbourhoods with shapes that resemble peninsulas (Figure 5). Câmpina City and Urziceni City constitute counterexamples as they do not fit the aforementioned pattern. Although its urban built-up area presents a peninsular feature in the NE, the high street density and the compact shape of the rest of the urban territory determine a favourable distribution of distance-based polygons in Câmpina City, with more than 75% of the city within 3000 m of the hospital (Figure 4). Moreover, in Urziceni City, there are no areas of very low accessibility, possibly due to the small dimension of the urban territory (Figures 4 and 5).

Another element that decreases accessibility in certain parts of the urban area, even in compact-shaped cities, is the presence of the railways. If they are not crossed by level crossings, railroads tend to isolate neighbourhoods located on the side that is further from the medical unit. In Adjud and Bârlad cities, the railways located in the E part of the urban territory isolate the E and SE industrial areas, while the railways in Tecuci reduce accessibility to healthcare centres for the residents located in the SW and NW part of the city (Figures 3 and 5). On the other hand, the level crossings of the E railway in Râmnicu Sărat moderate the limitation effect of railways. Additionally, there are cities where the marginal position of the railroads does not affect accessibility levels but where other natural barriers lead to this outcome (e.g., the forest strip in the SW of Câmpina).

Settlements with more than one healthcare unit are characterised by different spatial configurations of medical service areas, which are influenced not only by the position of these units but also by their spatial dispersion. In Bacău and Ploiești, the centrally positioned but dispersed medical facilities determine a radial extension of the service areas. On the contrary, the clustering of hospitals in a marginal position determines the skewed configurations of service areas. For instance, the NW cluster of medical facilities in Onești and the NE cluster in Focșani determine a N–S extension of the service areas, which is the opposite of the S–N extension of the medical service area in Buzău City.

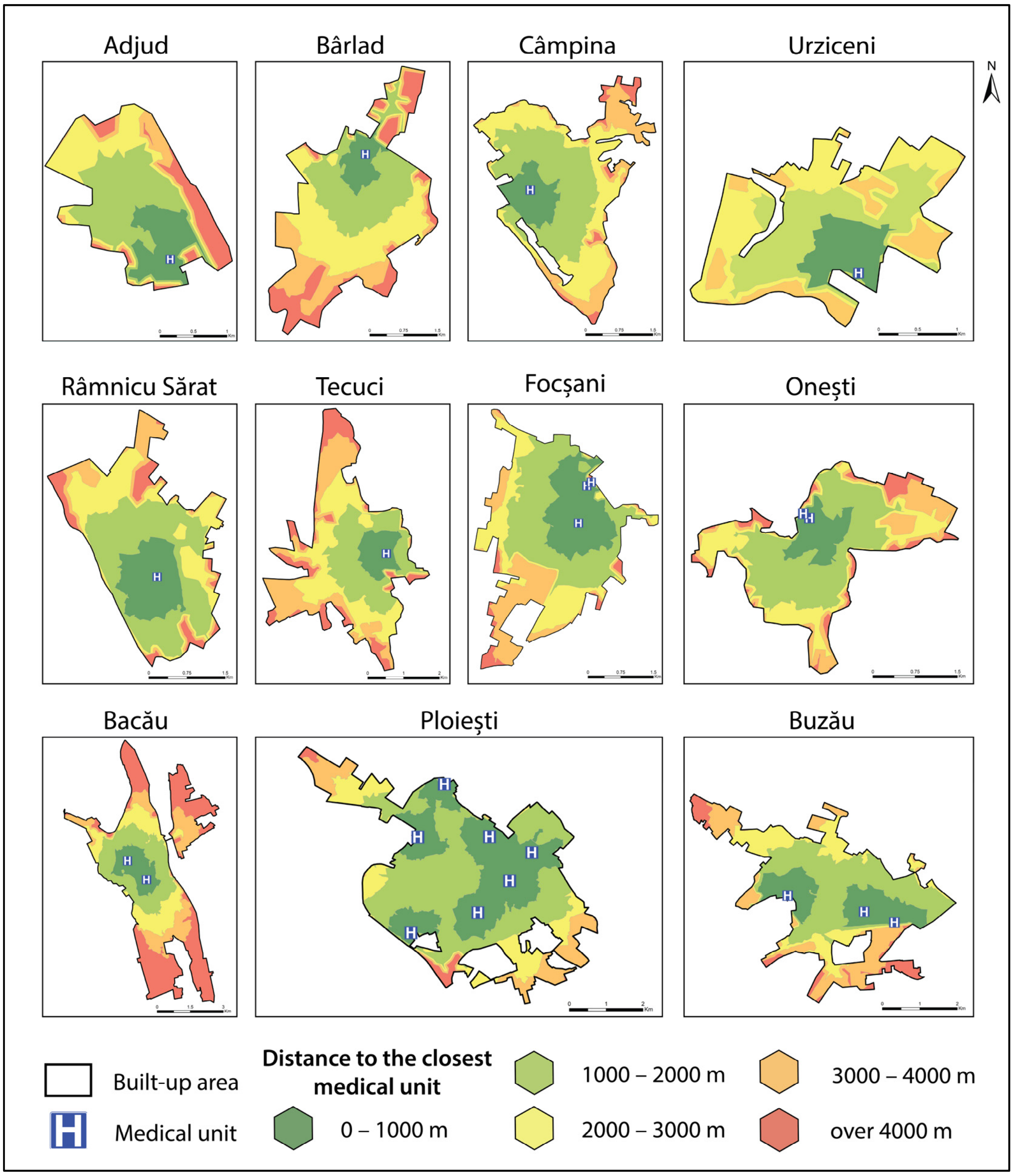

Figure 5. The service areas of the medical units in the 11 urban settlements. Service areas extend towards medical facilities. The scale was adapted for each urban settlement to better portray the service areas.

Figures 4 and 5 show that cities served by many healthcare facilities present large areas (over 50% of the urban territory) with very high and high accessibility (i.e., Ploiești, Focșani, Buzău, Onești), although the shape of their territories may be convoluted. Nevertheless, the peninsular configuration of the urban territory of Bacău determines smaller areas with higher accessibility (covering about a third of the total) despite the fact that the two medical units are centrally positioned (Figure 5). Other patterns refer to the continuity or discontinuity of areas with very high accessibility levels. In cities with medical facilities located close to each other (i.e., Focșani and Onești), the dark green area is continuous, and there is only one "island" of very high accessibility. The opposite pattern is observable in more populous cities, where the very high accessibility areas are discontinuous, and two (i.e., Buzău) or even three (i.e., Ploiești) “islands” of dark green are present due to the significant spatial dispersion of healthcare facilities.

In terms of low-level accessibility, only Bacău City presents extensive areas of very low accessibility (over 36%), while in the other urban settlements with multiple medical units, this level accounts for less than 7.5% of the territory (Figure 4). Similar to cities served by only one medical unit, convoluted urban shapes are responsible for the emergence of peripheral, peninsular areas of lower accessibility: the S peninsulas in Ploiești, Buzău, Focșani, Onești, and Bacău. In certain cases (e.g., Ploiești, Buzău), the accessibility limitation effect of the peninsular configuration is compounded by low street density and by the presence of railways. There are also cases where the limitation effect of railroads is rather weak, such as in Bacău City, where centrally located railroads have a minor impact on accessibility in the central area, owing to the numerous level crossings.

An aspect worth mentioning refers to the islands of lower accessibility levels that lie within areas of higher accessibility. These can be observed in Bacău, Bârlad, Râmnicu Sărat, Tecuci, Onești, Focșani, Câmpina and Urziceni (Figure 5) and can be considered mapping artefacts determined by lower street densities specific to military or police units, railway areas, parks, or sports fields.

4.2. Accessibility to Fire Stations

Because there are fewer fire management facilities, accessibility patterns are less favourable than for medical units. Figure 4 shows that fewer urban settlements have over or about 50% of their territory located no more than 2000 m of the closest fire station (i.e., Adjud, Bârlad, Focșani, Râmnicu Sărat). Nonetheless, the distance-based polygon with the largest general extent is the same as in the case of medical units (i.e., high accessibility associated with 1000–2000 m distance). Adjud City displays the most favourable situation, having almost 70% of its territory within 2000 m from the closest firefighter detachment unit due to the compact shape of the urban territory and high-density street network. On the contrary, about 70% of Bacău City is located more than 3000 m away from the nearest fire station, which is mainly explained by the convoluted shape of the urban territory. The better parts of Bârlad and Focșani cities (more than 50%) are also located no more than 2000 m away from fire stations. However, despite having two fire management facilities within its urban territory, less than 35% of Ploiești City accounts for the higher accessibility levels (Figure 4).

In cities with fire stations that hold central positions, service areas unfold in a radial manner (i.e., Bacău, Bârlad, Buzău, Focșani, Tecuci), while the marginal positions of these key facilities determine skewed configurations (i.e., Urziceni, Ploiești, Câmpina, Râmnicu Sărat, Adjud, Onești) (Figure 6). In Ploiești and Râmnicu Sărat, the distance-based polygons of the service areas extend from S to N, while the unfolding of the service area in Onești follows the opposite direction. Also, in Adjud, Câmpina and Urziceni, the service areas extend from W to E.

Areas of very high and high accessibility, located no more than 2000 metres from the nearest fire management centre, tend to occupy central positions with varying extents in Bârlad, Focşani (more than 50% of the territory), Buzău, Tecuci (more than 35%), and Bacău (less than 15%) (Figures 4 and 6). Except for Ploiești City, where the two fire stations and the S peninsular configuration determine two “islands” of very high accessibility, coloured in dark green (Figure 6), the urban settlements display continuous areas with such levels of accessibility.

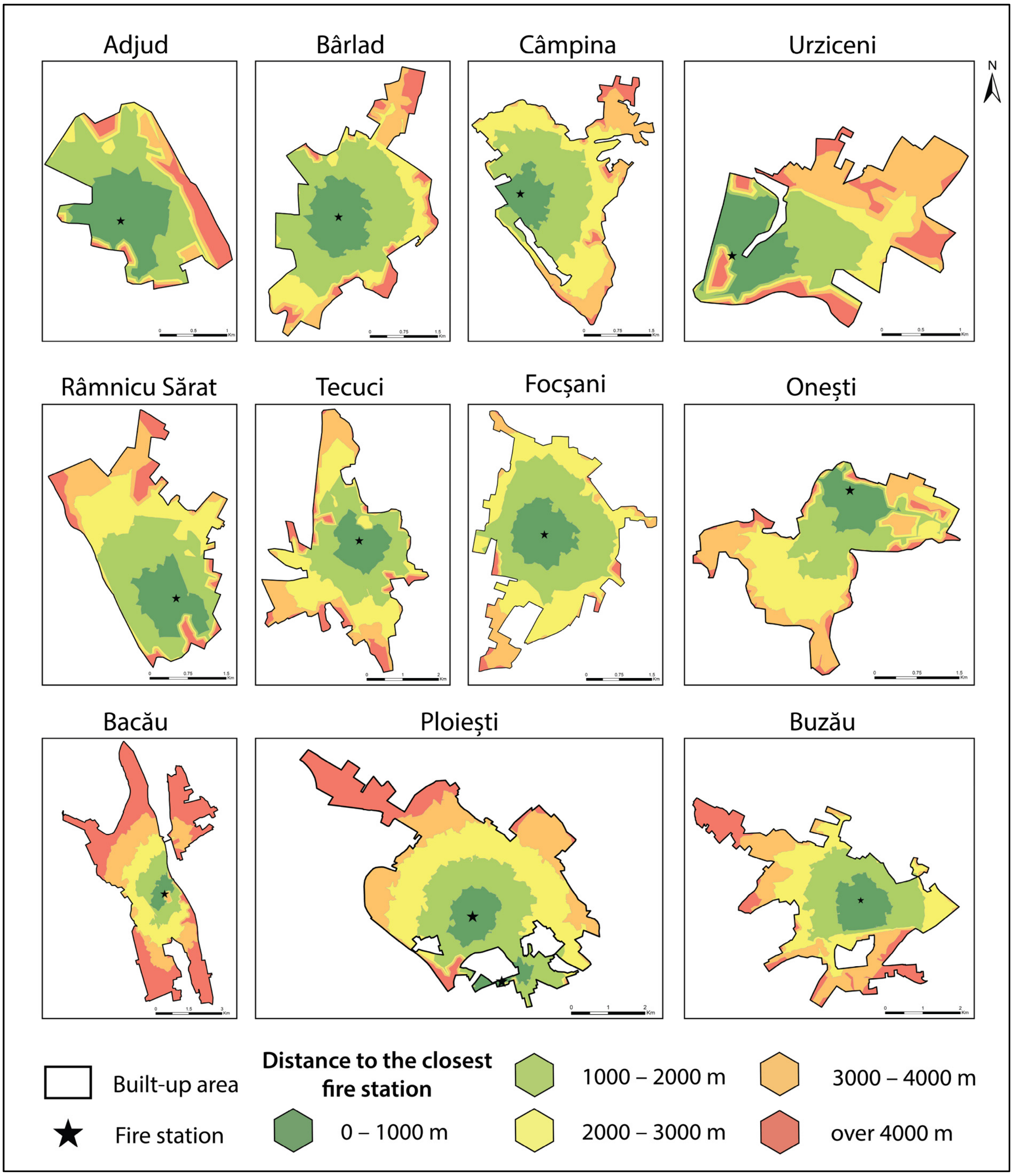

Figure 6. The service areas of the fire stations in the 11 urban settlements. Service areas extend away from fire stations. The scale was adapted for each urban settlement to better portray the service areas.

Very low and low accessibility levels account for large proportions of Bacău, Urziceni, Buzău, Ploiești, and Onești (more than a third of the urban territory), which display complex-shaped urban territories (Figures 4 and 6). Lower accessibility areas are least extensive in Focșani (about 11%), possibly due to the central position of the fire station and of the dense urban street network. Such accessibility levels are usually recorded in peninsula-shaped neighbourhoods (i.e., in Bacău, Bârlad, Tecuci, Focșani, Onești, Buzău, Câmpina, Ploiești), but there are other compact peripheral areas characterised by such levels. These are the result of low street density characteristics to certain land covers (i.e., in Bârlad, Râmnicu Sărat, Adjud, Buzău, Câmpina), which may be corroborated by the accessibility limitation effect of railways (i.e., in the N part of Urziceni, E part of Adjud, SE of Bârlad) (Figures 3 and 6). In fact, railways tend to reduce accessibility to fire stations in many of the analysed urban areas, having strong effects in the mentioned cities, as well as in Tecuci and, Buzău, and a weaker effect in Bacău, Râmnicu Sărat (due to the fact that railways are crossed by many level crossings), and Focșani (due to the marginal W position of the railway). Ploiești City represents an interesting case where the railways in the NE reduce accessibility, but the ones that cross the S part of the city have a very weak accessibility limitation effect, mainly because they lie between the two fire stations and present multiple level crossings (Figures 3 and 6).

Similar to the case of accessibility to medical units, the maps illustrating the service areas of fire stations present "islands" of lower accessibility located within areas of higher accessibility (i.e., Bacău, Adjud, Tecuci, Onești, Urziceni, Râmnicu Sărat, and Câmpina) (Figure 6). The most prominent feature of this type is located immediately to the S of the fire station in Bacău City, where the urban street density is reduced, limiting the extension of the very high accessibility area to the N.

4.3. Patterns of Earthquake Systemic Vulnerability

The proportion and coverage of earthquake systemic vulnerability levels within the analysed cities result from the overlaying of accessibility to medical units and fire stations. Figure 7 provides an overview of the area percentages specific to five vulnerability levels that inversely match the accessibility ones (Figure 2, Section 4), pointing out both favourable and less desirable situations in terms of systemic vulnerability. Nevertheless, the most prominent vulnerability level in terms of coverage is low vulnerability (2), covering over a third of the urban territory of Adjud, Focșani, Urziceni, Bârlad, Râmnicu Sărat, Câmpina, and Buzău. This level of systemic vulnerability is due to the dominance (and overlap) of areas characterised by high accessibility to medical units and fire stations (Figures 5, 6 and 8).

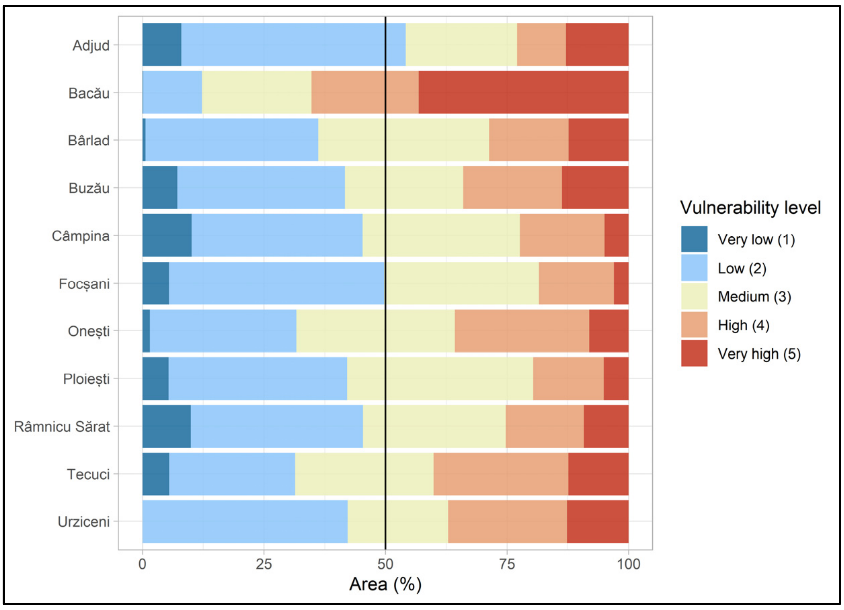

Figure 7. Areas (as percentage of urban territory) of systemic vulnerability levels, in the 11 urban settlements.

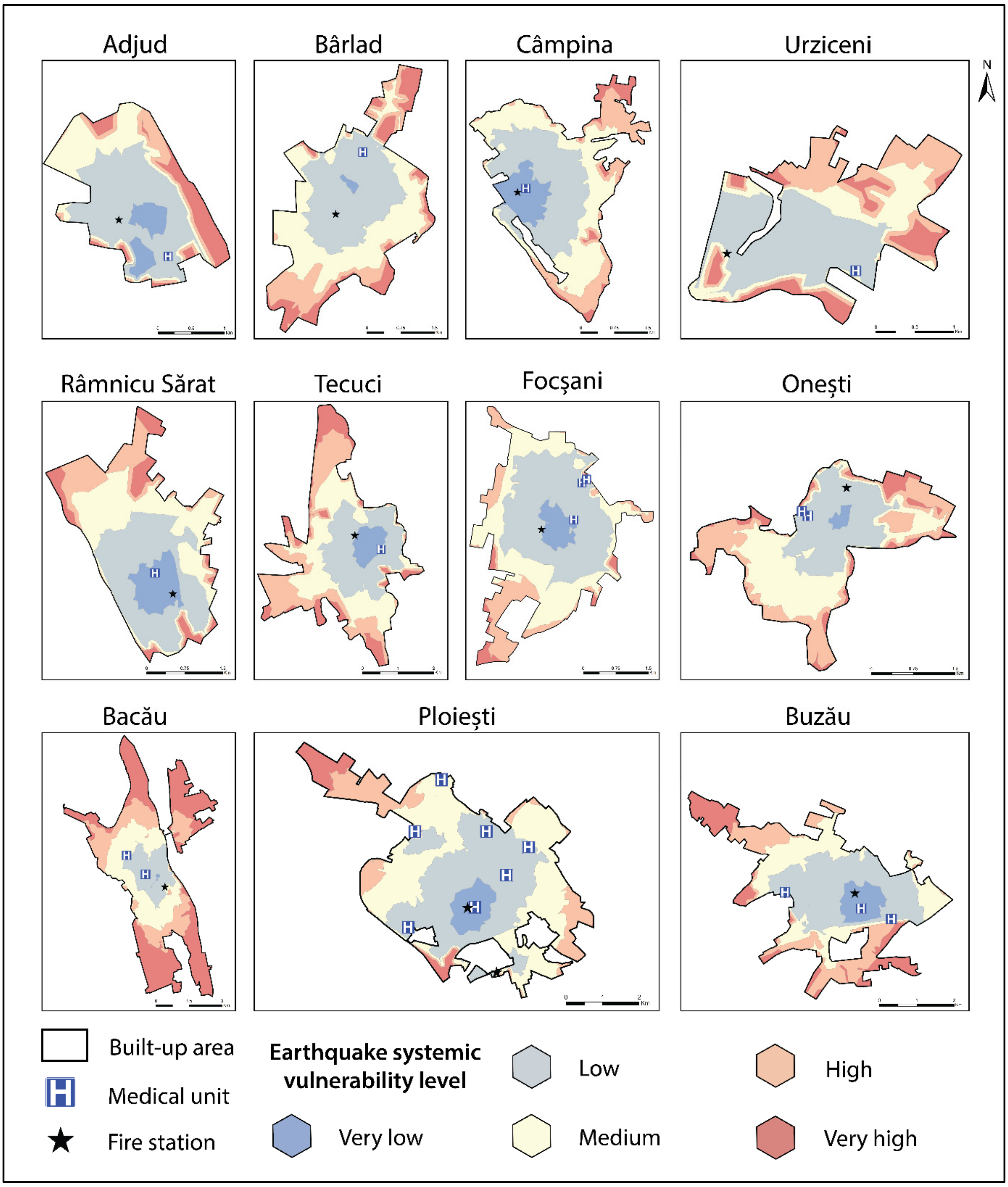

Figure 8. Earthquake systemic vulnerability maps of the 11 urban settlements. Vulnerability increases outward from the medical and fire management facilities. The scale was adapted for each urban settlement.

The spatial configuration of systemic vulnerability is dependent on the overlap of different accessibility levels, which in turn is heavily influenced by the position and dispersion of key emergency management facilities. For example, areas characterised by very low systemic vulnerability appear where two areas of very high accessibility to medical units and fire stations overlap. Additionally, large overlaps between areas with very low accessibility to medical centres and fire stations lead to increased vulnerability levels. This means that facilities of different types with a small to medium degree of spatial dispersion determine larger areas of very low vulnerability (especially if the facilities are located in a central position). On the other hand, facilities of different types that are too dispersed (i.e., separated by great distances), eventually holding a marginal position, determine the opposite outcome. The first situation may be observed in the cases of Adjud, Focșani, Câmpina, and Râmnicu Sărat, where the lower vulnerability levels account for 45–54% of urban areas (Figure 7). The latter case is illustrated by Urziceni City, where the Municipal Hospital and the fire station hold opposite marginal positions (Figure 8), so there is no overlapping between very high accessibility areas, hence no areas with the minimum level of vulnerability (Figure 7). Ploiești City is representative of the in-between situation, having medical units and fire stations spread out within the urban territory but not at a great distance (Figure 3), which explains the extensive coverage of lower vulnerability levels (about 42% of the urban territory).

Adjud City shows the most favourable situation since more than half of its territory has very low vulnerability levels (Figure 7); this is motivated by a balanced spatial distribution of the hospital and fire station (which also have central positions), meaning that they are scattered within the territory, but the distance between them is not too long. This is complemented by the compact shape of the urban territory and its reduced extent. Because of the aforementioned factors, there is a significant but discontinuous overlap of high accessibility areas (Figure 8).

The record for the opposite systemic vulnerability level belongs to Bacău City, where almost 65% of the territory presents very high and high vulnerability, and only 0.12% of it is characterised by very low vulnerability (Figure 7). This is the result of the intricate spatial configuration of the urban area as a whole, corroborated by the linear, short-distance placement of the facilities of interest (Figure 8). Although these facilities are centrally located and should favour a larger area of very low vulnerability, the low street density to the S of the fire station determines the extension of the high accessibility area to the N, which in turn reduces the overlap with the area characterised by the same level of accessibility to the medical units (Figures 5, 6 and 8).

Other urban settlements with large areas of very high and high vulnerability are Tecuci and Onești (35–40% of the territory), where the peninsular features in the first case, which are complemented by the high dispersion of key facilities marginally positioned in the latter case, determine a significant overlap of areas with very low and low accessibility to emergency management units of different types (Figure 8). The same situation can be observed in Urziceni, but for different reasons: the extremely high degree of dispersion of facilities in the opposite marginal position, which is backed up by the accessibility limitation effect of railroads.

The position of key emergency management centres also dictates the direction of the increase in systemic vulnerability. Where facilities of different types are located close to the geometric centre of the urban territory, vulnerability increases in a radial direction (i.e., Bacău, Buzău, Ploiești, and Focșani) (Figure 8). Increases that follow directions defined by opposite cardinal points are also common: vulnerability increases from N to S (i.e., Bârlad, Onești), from S to N (i.e., Adjud, Râmnicu Sărat), from E to W (i.e., Tecuci), or from W to E (i.e., Câmpina). Urziceni makes up a special case in this regard since the marginally opposite positions of the hospital and fire station add up to increase the systemic vulnerability following a radial spatial pattern.

The areas with very low vulnerability are continuous in most of the cases (i.e., Bârlad, Buzău, Ploiești, Focșani, Câmpina, Onești, Râmnicu Sărat, and Tecuci). In the particular case of Adjud City, two "islands" of dark blue colour can be observed, which means that the area of very low vulnerability is discontinuous (Figure 8). Another deviation from the norm is specific to Bacău City, where the area of very low systemic vulnerability is composed of small "islands" (covering only 0.12% of the urban territory), which may be mistaken for mapping artefacts. These configurations also result from the position and dispersion of emergency management centres: the very low vulnerability areas may emerge in between facilities of different types that are located at a fair distance (i.e., Adjud, Bacău, Bârlad, Râmnicu Sărat, Tecuci, Onești, and Focșani) or may extend from a cluster of very close medical unit(s) and fire station(s) (i.e., Buzău, Ploiești, and Câmpina) (Figure 8). However, when the distance between two facilities of different types is too large, no very low vulnerability area can form (i.e., Urziceni).

Higher systemic vulnerability levels are the result of overlapping areas with very low or low accessibility to medical units and fire stations. These are specific to peripheral urban areas resembling peninsular features in Bacău (in the NW, N, NE, SW, SE), Bârlad (N), Buzău (S, SW, NW), Ploiești (NW, SW), Râmnicu Sărat (NE), Tecuci (N, NW, SW, S), Onești (NW, S), Câmpina (NE), and Focșani (NW, S) or having low street density specific to different land covers (i.e., in Adjud, Bârlad, Râmnicu Sărat, Câmpina, Urziceni) (Figures 5, 6 and 8). In some cases, higher levels of seismic systemic vulnerability are determined by a convergence of factors, such as the peninsula-shaped urban areas and the accessibility limitation effect of railways (i.e., in the S and SW of Buzău and SW of Ploiești and Tecuci), or the low street density combined with the effect of railways (i.e., in the E of Adjud, E and SE of Bârlad, NW and W of Focșani) (Figures 3 and 8). In addition, certain "islands" of higher vulnerability levels may be observed within areas of lower vulnerability as a consequence of the overlap of such "islands" of accessibility to medical centres and fire stations (e.g., Bacău, Onești, Tecuci, Urziceni, and Focșani).

As mentioned before, railroads tend to act as accessibility barriers to emergency management centres, especially in peninsula-shaped areas or where they are uncrossed by level crossings. This acts as an enabler of increased systemic vulnerability, which may be easily observed in several of the analysed cities (e.g., Adjud, Bârlad, Tecuci, Onești, and Urziceni), and to a lesser extent in others (e.g., Râmnicu Sărat and Focșani) (Figures 3 and 8).

5. Discussion

The findings described in the last section indicate that the patterns of accessibility to medical units are more favourable than the ones specific to accessibility to fire stations (Figure 4), which is partly motivated by the higher number of healthcare facilities and the very low number of fire management facilities that operate at the local level (Figure 3). However, the overall accessibility of emergency management centres should not be a cause for concern because the distance-based interval with the greatest coverage in most of the studied cities is 1000–2000 m to the nearest facility (i.e., a high accessibility level). Therefore, earthquake systemic vulnerability may be estimated at a low to medium level, with the better part of the urban area under analysis having low vulnerability.

Nevertheless, when zooming in on the maps of service areas specific to medical units and fire stations and on systemic vulnerability maps, the observed accessibility and vulnerability patterns may deviate from the overall favourable situation. Of the 11 urban settlements, Adjud City presents the most desirable situation in terms of earthquake systemic vulnerability, which can be traced back to the convergence of the most favourable situation in terms of access to fire stations and one of the best situations in terms of access to medical units. This results from the medium degree of spatial dispersion of the emergency management centres (Figure 8), the compact shape (Figure 3), and the small extent of the urban territory, which allowed for an extensive overlapping of areas with higher accessibility to medical units and fire stations. On the other hand, Bacău City is the most vulnerable to earthquakes from a systemic point of view, ranking last in terms of accessibility to emergency management centres. The convoluted shape of its urban territory, defined by numerous peninsular features (Figure 3), together with low street density areas with central positions, ponderously influence both accessibility and vulnerability (Figures 5, 6 and 8).

Larger cities usually benefit from more key emergency management facilities, which increase accessibility and reduce vulnerability in theory, but in practice, the position and spatial dispersion of these facilities have to be taken into consideration too. Small cities served by one healthcare unit and one fire station tend to record higher vulnerability levels in large areas if they have complex-shaped territories (i.e., Tecuci, Onești, and Urziceni), but the same situation may be encountered in larger cities with more facilities (e.g., Bacău). Following the same logic, compact shapes of urban built-up areas favour higher accessibility and lower vulnerability (e.g., Adjud and Râmnicu Sărat). In addition, there are several factors (i.e., the presence of railways or natural barriers and land covers with low urban street density) that reduce accessibility and amplify vulnerability, regardless of the shape of the urban built-up area or the number, position, and dispersion of key emergency facilities. It should be highlighted that none of these factors has the same effect (be it attenuating or boosting accessibility/vulnerability) if taken separately and that it is difficult to determine which one has the highest relative importance, for their influences differ in power and direction from case to case.

The paper is one of the few to put systemic vulnerability under the magnifying glass since the component is usually integrated together with other dimensions of seismic vulnerability, which are assessed relying on Multi-Criteria Decision-Making methods [22,24,26,70], Machine Learning models [27,29], or a combination of the two [63]. In this case, accessibility is placed at the core of systemic vulnerability, similar to the assessments performed by [24–26] and [64]. However, there are studies that combine accessibility with road functionality impairment [64,71] or that rely only on road network functionality [30–35], but these elements were not included in the present spatial analysis due to the fact that building stock datasets were not available for all of the considered cities.

This is the first paper to address the systemic vulnerability of urban settlements in the study area and one of the few that focuses on this matter in a high-seismicity European context [28,30,31,34,35]. The absence of similar previous findings related to the study area limits the comparison of the presented results to the cases of Focșani and Bârlad cities. These cities were taken under analysis by [28], who developed an Earthquake Systemic Vulnerability Index based on indicators referring to the accessibility of emergency services centres, the capacity of the local medical infrastructure, and secondary danger sources. According to this index, Focșani City presents a low-level systemic vulnerability, ranking second to last in this regard among the administrative urban centres in the SE region of Romania. On the other hand, Buzău City ranked second in terms of earthquake systemic vulnerability [28]. These levels of systemic vulnerability are concordant with the ones presented in the Results section (Figure 7).

This study contributes to the research field of earthquake vulnerability by adding important insights on spatial patterns of systemic vulnerability, which can be used to ground and guide decision-making in emergency management. Such findings substantially add to our understanding of urban space-dependent vulnerability sources, and their value is supported by multiple integration opportunities, among which the following are the most important:

- The identification of the most vulnerable neighbourhoods (from a systemic point of view), which is crucial for planning optimal paths for emergency interventions prior to the manifestation of seismic events;
- The identification of urban areas that would benefit from the placement of secondary fire stations and/or new/temporary medical facilities, or even earthquake shelters;
- The identification of urban areas where educational programmes concerning earthquake adjustments, evacuation, and protection should be implemented with priority.

The relevance of the results, seconded by the necessity to use them to improve strategies that focus on earthquake impact mitigation, are underpinned by (i) the high-level seismic hazard of the study area [40,52] and (ii) the insufficient, incipient-stage knowledge regarding earthquake vulnerability in the study area. As mentioned before, only Focșani and Buzău cities have been studied in terms of seismic systemic vulnerability [28], which means that the present study literally puts nine more Romanian urban settlements on the map. Thus, the paper contributes to the positive transformation of the predicament, for which the lack of knowledge on urban seismic vulnerability is partially responsible [41] in a country that faces significant seismic risk.

Another noteworthy contribution of the study is that it provides an open source data-based methodological framework (Figure 2) that can be implemented to identify spatial patterns of systemic vulnerability in other areas with high seismicity. By integrating hands-on data concerning healthcare and fire management facilities, urban street networks, and land cover, the necessity to adapt the methodological framework to site-specific conditions is eliminated, making the framework transparent and universally replicable. The methodological framework proves to be valuable, especially for urban settlements that were not (sufficiently) explored in terms of earthquake vulnerability, as it uses readily available data from OSM and provides a diversified range of valuable outputs: a primary view on accessibility-based vulnerability levels, maps, coverage data, and visual representations of different accessibility and vulnerability levels.

Nevertheless, the merits of the study should also take into account its limitations:

- Caution is advised when interpreting the results since the analysis operates only with one component (i.e., systemic vulnerability) of the multifaceted vulnerability concept. For example, cities with high levels of systemic vulnerability may prove to be less vulnerable to earthquakes overall if their building stock is robust enough to limit damage, hence the injuries and the number of fatalities—"Earthquakes don't kill, built environment does" [72]—and the need for emergency interventions. Additionally, the study does not account for socio-economic vulnerability, which heavily influences the number of people that may actually need emergency interventions.
- Another limitation relates to the operationalisation of systemic vulnerability relying solely on accessibility and not integrating the capacity and/or functionality of emergency management facilities in a post-seismic context. A major earthquake may cause structural damage to hospital buildings [73] or firefighters' quarters [74], also threatening the lives of key personnel (i.e., doctors, medical assistants, firefighters, intervention drivers, etc.). Capacity and functionality can still be impaired (even if emergency centres are not directly affected by earthquakes) when the workload prior to the manifestation of the seismic event is too much to manage to begin with, as in the case of increased pressure caused by the COVID-19 pandemic [75,76].
- The methodological framework deliberately leaves out time-dependent variables such as traffic or population exposure, which would require specific datasets that are not available in many developing countries, including Romania. This may be considered a research design-related limitation, which was tackled by tailoring the methodological framework to provide a diversified set of results that can serve as primary information that can be used to improve vulnerability reduction plans at the local and regional scales.
- Finding validation procedures for the results of the presented spatial analysis proves to be a tall order, for which the outcomes of future earthquake events may be used as a comparison. Nevertheless, the results of this research work are not based on scenarios but only aim to provide an overview of the seismic systemic vulnerability patterns specific to the urban settlements in a high-seismicity European area.
- Future research directions should consider the integration of road impairments that may be caused by building collapse with accessibility to emergency management centres. Such approaches have the benefit of increasing the robustness of the results by reducing the uncertainties inherent in vulnerability analyses, but they require datasets that are difficult to acquire, especially in Romania. For instance, cadastral data concerning the position and the horizontal and vertical extent of buildings should be integrated with road taxonomy in order to estimate building collapse, implicitly road functionality impairment. Unfortunately, such data are not readily available, and their collection has to rely on workarounds in the form of building stock datasets obtained via building objects delineation on high-resolution imagery through edge detection algorithms [77].

6. Conclusions

Focusing on the high-PGA area located at the bend of the Carpathian Arch in Romania, this paper plots 11 of the European urban settlements with the most urgent need to be explored in terms of seismic vulnerability on the map of earthquake systemic vulnerability. The accessibility-focused approach leads only to primary time-independent spatial patterns, but for the urban settlements located in high-seismicity areas that have not been (sufficiently) studied, these constitute the starting points of systemic vulnerability-related research. In other words, this paper marks the beginning of systemic vulnerability assessments in areas that should have already benefited from such research. The proposed open source data-based methodology, which can be replicated to identify spatial patterns of systemic vulnerability based on accessibility to the emergency management facilities with key responsibilities in the narrow post-earthquake timeframe, represents another scientific contribution of this research work.

Predictibly, the spatial analysis puts forward different accessibility and systemic vulnerability patterns for small cities with few emergency management facilities, and larger cities with more medical units and fire stations. However, such patterns are shaped by a combination of variable elements deeply rooted in the urban spatial layout, including the position and spatial dispersion of key emergency management centres, the shape of the urban built-up area, the configuration of the urban street network, the position and the extension of railroads or other natural barriers. Therefore, local-scale particularities should not be neglected when analysing vulnerability patterns, but rather viewed as key elements of such analyses. The multi-faceted convergence of these factors results in unexpected accessibility patterns; as in the case of Bacău City, where the intricate layout of the urban built-up area, the cental areas with low street density, and the spatial discontinuity created by the river generate premises for high systemic vulnerability levels. Smaller cities, on the other hand, with more compactly shaped urban areas and higher urban street density, have lower systemic vulnerability levels (e.g., Adjud, Focșani, Râmnicu Sărat).

Knowing ahead of time which urban areas will be the most difficult for emergency response teams to reach, or where temporary healthcare facilities and secondary fire stations should be located, aids in the development of improved, locally-adapted earthquake vulnerability reduction strategies. Furthermore, such findings can aid in the allocation of financial and human resources at the regional scale in advance, allowing authorities and emergency management services to make scientifically sound decisions.

Since systemic vulnerability can be reduced in a timelier manner and at a lower cost than other dimensions of earthquake vulnerability (e.g., structural vulnerability), the results of this study can be integrated into early on efforts aimed at reducing seismic vulnerability, acting as change generators. Further to that, by modifying spatial patterns of systemic vulnerability, negative outcomes associated with structural or socioeconomic vulnerability can be mitigated. Thus, understanding and modelling one component of seismic vulnerability not only solves specific problems, but also raises awareness about the interconnected challenges that result from various vulnerability facets.

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