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Spectroscopy of Urban Vulnerability

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Abstract: Despite the considerable work carried out in risk management, vulnerability indexes and aggregative assessments remain a serious issue. The main challenges facing vulnerability assessment are the collection, integration and synthesizing of large quantities of heterogeneous data in order to provide reliable estimations. This situation has led to the neglect of all significant interactions between the considered indicators, despite their being essential to vulnerability analysis. The scope of the paper is to show that most obstacles to vulnerability assessment can be overcome by shifting the focus from absolute vulnerability assessment, i.e. the attempt to quantify an absolute level of weakness or resilience, to relative vulnerability assessment, i.e. the attempt to find out which populations and places are vulnerable and why. We propose a first attempt to assess relative vulnerability. The Social Vulnerability Profiles (SVP) reveal the heterogeneity of vulnerability by focusing on the locally convergent specific characteristics and processes reinforcing (or reducing) vulnerability in order to inform the implementation of more targeted mitigation policies. This is a two step approach, first focusing on the vulnerability underlying factors and establishing vulnerability profiles; and then the second step is to focus on their spatial distribution in order to confront each vulnerability profile to its multi-threat exposure. The Lyon, France, and Bucharest, Romania, case studies reveal the risk transfers induced by some risk management policies and they highlight that vulnerability is a multidimensional phenomenon almost impossible to assess by using a single index. The two cities also permit local multi-threat comparisons as well as international comparisons.

Key Words: *risk; hazards; vulnerability assessment; GIS; Lyon, France; Bucharest, Romania.*

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The 1990s were dedicated by the UN as the International Decade for Natural Disaster Reduction and this led to a large number of publications related to risks, their management and mitigation. The decade also saw vulnerability becoming a key concept (Cutter 2001), with megacities increasingly seeing this issue as a major challenge facing the 21st century (Mitchell 1999). During the last fifteen years, much attention has been paid to a new definition of concepts. And more recently, an increasing number of projects have been developing vulnerability assessments and indexes from local to global scale, such as the Vulnerability-Resilience Indicator (Moss *et al.* 2002), the Predictive Indicators of Vulnerability Index (Adger *et al.* 2004), the Social Vulnerability Index (Cutter *et al.* 2003), and the Environmental Vulnerability Index (Kaly *et al.* 2004). However, despite all these theoretical and methodological efforts, as well as the considerable work carried out to attempt to reduce disasters and losses, the problems continue to intensify and are accompanied by failures to forecast, to reduce impacts or even offer reliable tools to inform policy (White *et al.* 2001; Cutter 2003; Birkmann 2006; Hartman *et al.* 2006; Barnett *et al.* 2008).

As Barnett *et al.* have pointed out, vulnerability “*is an imprecise term with intuitive resonance, if no single definition*” (2008, 103). The field has significantly evolved from its foundations in hazard studies (Burton *et al.* 1978) and its following critiques for a lack of attention to structural conditions (Hewitt 1983). In earlier studies, vulnerability was strongly associated with the potential for loss and hazards exposure, implying that risk is of an external nature (UNDRO 1982). Vulnerability studies have then explored the spatial and social distribution of losses to disclose the discriminating sensitivity to disasters, reducing people to being passive recipients or even helpless victims (Mitchell *et al.* 1989; Palm 1990). More recent vulnerability studies have approached vulnerability more as a societal response and not only as a biophysical condition. The two most prevalent frameworks can be seen as complementary (Eakin *et al.* 2006). The pressure and release model examines who is vulnerable and why by tracking the underlying drivers of vulnerability on the social, political, and economic pressures, the root processes constraining the ability of individuals to cope with disasters (Blaikie *et al.* 1994; Wisner *et al.* 2004). The hazard of place model describes the place-based relationship between hazard exposure and the underlying socio-economic processes and demographic characteristics of the local population (Cutter 1996). Increasingly, even scholars from outside the field of social science acknowledge that disaster mitigation require a better understanding of the differential impact of hazards as a product of the socially constructed vulnerabilities of specific groups (Neumayer *et al.* 2007; Morrow 2008). However, Mitchell has pointed out the disadvantage of these analytical approaches of vulnerability drivers (1999): they are interconnected and provide thus an interactive context to disasters. As a result, Cutter *et al.* (2003) and Turner *et al.* (2003) have proposed a more integrative approach, focusing on the place-based convergence of interacting vulnerability characteristics, such as poverty, unawareness, poor building resistance and multi-threat exposure, and locating local vulnerabilities within the larger contexts that influence processes often operating at broader scales.

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We adopt the definition of vulnerability as “*the characteristics of a person or group and their situation influencing their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard*” (Wisner *et al.* 2004, 11). And following the place-based approach, we focus on the interactions between the different dimensions of vulnerability, their underlying drivers, and the feedback from hazards exposure and previous disasters. Physical (or biophysical) vulnerability refers to the degree of resistance of a building or a society to a dangerous phenomenon by deepening the sensitivity approach (Turner *et al.* 2003; Birkmann 2006; Eakin *et al.* 2006). Social vulnerability refers to the incapacity of individuals to cope with crisis or change. For this reason, vulnerability is sometimes brought closer to the concept of resilience. However, the concepts of vulnerability and resilience are complex and their meanings are often contested. While vulnerability is widely considered to be the opposite of resilience (Barnett *et al.* 2008), for some, resilience is part of vulnerability (Burton *et al.* 1978), whereas, for others, it is defined as the adaptive capacity (Holland 1995), or in opposition to anticipation (Wildavsky 1988). The problem is that one can be vulnerable to an impact while being subsequently resilient (Adger 2000). In a sense, this is because a society is vulnerable that it will suffer crises that it will have to face up to, adapt and learn from disasters. Moreover, there is still no agreement about the properties that enable resilience; so there are no robust models on which indicators can be developed (Comfort *et al.* 2010). Consequently, we stick to the concept of vulnerability which seems both broader and more robust to us. Finally, we are also considering the critical infrastructures (hospitals, schools, etc.) and networks (transport, supply networks etc.) as indicators of the functional dimension of vulnerability: their dysfunction or destruction worsens every crisis and impedes reconstruction (Kasperson & Kasperson 2005; Quarantelli 2003). These infrastructures and networks have a dual interest. On one hand, they represent a significant concentration of individuals, a factor that automatically increases the number of people potentially exposed to hazards and complicate the crisis management and evacuation procedures (Rodriguez & Quarantelli 2007). On the other hand, they also reveal the junctions that can spread the crisis in a reticular manner or cause a change in the scale of the crisis (from local to regional).

These various dimensions of vulnerability are interlinked and denote the increasing complexity of processes associated with manifestations of vulnerability, at the interface of social and ecological systems. However, vulnerability assessments are based on aggregate approaches that eliminate this complexity and these local interactions. They are “*imperfect and do not reflect the reality they seek to convey*” (Barnett *et al.* 2008, 107). This gap between the in-depth renewal of the conceptual instrument and the epistemological challenges facing vulnerability assessment methods, comparisons and mapping, demands further exploration. The purpose of this paper is to show that most obstacles to vulnerability assessment can be overcome by shifting the focus from absolute vulnerability assessment, i.e. the attempt to quantify an absolute level of weakness or resilience, to relative vulnerability assessment, i.e. the attempt to find out which populations and places are vulnerable and why. We shall begin with a presentation of the methodological obstacles to vulnerability assessment, continue by proposing a first attempt to assess relative

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vulnerability and, finally, the different outcomes offered by a relative vulnerability assessment are illustrated by two European case studies in Lyon, France, and Bucharest, Romania. The first case study shows that relative vulnerability assessment leads to a shift in focus from the places most exposed to various hazards and sources of danger to the most vulnerable neighbourhoods, and it also reveals the risk transfers induced by some risk management policies. The second case study demonstrates that vulnerability is a multidimensional phenomenon almost impossible to assess by using a single index; it reveals a bipolarisation of vulnerability that calls for differentiated mitigation measures.

Methodological Obstacles to Vulnerability Assessment

The various dimensions of vulnerability require that a considerable amount of different types of data from a wide range of sources be taken into consideration. Consequently, the main challenges facing vulnerability assessment are the collection, integration and handling of large quantities of heterogeneous data. The first difficulty facing assessments methods lies in the challenge to reduce the complexity of interrelated characteristics and processes to a particular variable or set of variables; and some of them are very difficult to quantify (Barnett *et al.* 2008). Then, indices and indexes are very sensitive to the selection of data able to reflect the complexity of multi-hazard exposure, the specificities of the weaknesses inherent in the exposed systems (high density, obstruction of networks, etc.), and the social capacities of adaptation and risk mitigation (Jones *et al.* 2007). Furthermore, this data may be difficult to access, unreliable or incomplete, especially in the case of international comparisons (Cardona 2005). Finally, assessments methods also encounter formal problems in the synthesizing of all this data and the ability to provide reliable comparisons (Barnett *et al.* 2008; Birkmann 2006; King 2001; Villa *et al.* 2002; Schmidlein *et al.* 2008; Turner *et al.* 2003). Recent studies have presented three types of solutions for overcoming methodological obstacles. These are based on accounting, analytical and synthetic approaches.

The accounting approach to vulnerability translates all data into monetary terms and assesses foreseeable damages in the event of a catastrophe (Flax *et al.* 2002; Linkov *et al.* 2004; OECD 2003). Its main field of application is insurance. However, it also results in confusion between vulnerability, hazard exposure and the estimated consequences of a disaster (Gilles 2004). In addition, it generates a large number of problems when the phenomena occurrence probability is unknown. Furthermore, it generates ethical problems when it concerns human loss of life, damage to infrastructures and the destruction of a cultural heritage, given that they are all estimated using the same monetary unit (Rodriguez & Quarantelli 2007).

The analytical approach relies on identifying and combining a set of “vulnerability underlying factors” or “vulnerability interacting drivers” (Cutter *et al.* 2003; Turner *et al.* 2003). It then proposes aggregate algorithms (Mos *et al.* 2002; Chakraborty *et al.* 2005; Schmitt-Thomé 2006; De Sherbinin *et al.* 2007) or matrix treatments (Mitchell 1999; Kaly *et al.* 2004) that allow comparisons to be made through the publication of vulnerability indices and indexes. However,

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the approach can suffer from the multiplication of heterogeneous indicators and the defining of arbitrary thresholds. Vulnerability indicators are added together or multiplied in different ways by different authors without taking their diversity and interactions into account. The result is that vulnerability is measured in an arbitrary, subjective and incomplete manner (Barnett *et al.* 2008). Even when interactions are considered as a relevant process in the creation and strengthening of vulnerability, the search for vulnerability metrics leads to the use of aggregate assessment models that eliminate interactions and the particularities of local situations (Schmidtlein *et al.* 2008).

The synthetic approach relies on systemic analysis to grasp, on one hand, the interacting root causes of vulnerability and, on the other hand, to assess risk management policies (Kreimer 2003). It transforms the analysis of vulnerability into an “interpretation key” but it is condemned to *a posteriori* analysis (Wisner *et al.* 2004; Pigeon 2005) given that it does not allow mapping or vulnerability assessment.

The handling and treatment of specific vulnerability databases are thus confronted with two main problems. On one hand, the different types of data and their various sources have to be rendered compatible. These attempts to reduce heterogeneity have either led to a uniform monetary translation or to integration within a single arbitrarily determined indicator. This situation has led to the neglect of all significant interactions between the considered indicators, despite their being essential to vulnerability analysis. On the other hand, and although not exhaustive, the number of vulnerability proxies taken into account has increased considerably with the development of data storage and treatment capacities. To overcome methodological obstacles, we should cease looking for a measurement scale and try adding together all indicators and drivers that might be involved in the various crises and disasters. However, we still need an all-hazard approach and a vulnerability assessment method that provides both mapping and comparison possibilities in order to inform the implementation of targeted mitigation policies.

From absolute to relative vulnerability assessment

We propose overcoming these various obstacles in two steps: first, by changing the point of view from absolute to relative vulnerability, and second by revealing the heterogeneity of vulnerability and focusing on the locally convergent specific characteristics and processes reinforcing (or mitigating) vulnerability rather than attempting to measure vulnerability by adding together of all available data.

The expression, “there is no zero risk”, can be transposed to vulnerability: there is no such thing as an invulnerable place, person or society. Consequently, vulnerability assessment is no longer an attempt to quantify an absolute level of weakness or the metrics of potential damage, but rather an attempt to find out which populations and places are vulnerable and why within spaces exposed to various hazards and sources of danger. Geographers are convinced that place-based approaches deliver a more accurate vulnerability assessment than additive approaches (Barnett *et al.* 2008; Cutter 1996; Turner *et al.* 2003). But the use of metrics and

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indexes to compare vulnerability from one place to another also leads place-based approaches to the homogenisation of places and the elimination of the complexity associated with vulnerability.

Vulnerability indexes have been increasingly criticized because they are oversimplifying the complexity and interconnectedness nature of components that generate vulnerability, and because they fail to detect the heterogeneity of vulnerability. “There are many challenges to simplifying and conveying the complex reality of vulnerability in the form of an index” (Barnett *et al.* 2008, 106). To produce a single index, diverse kind of data and multiple indicators typically need to be standardized, scaled, scored through different thresholds, weighted and aggregated. In addition to be inescapably subjective processes, a subjectivity that decision makers might not always appreciate, they homogenize places for the purpose of comparison (Adger *et al.* 2004). Moreover, there is the challenge to reduce the complexity of an interaction within a system to a particular set of variables (Cutter *et al.* 2008). These indexes are highly dependent on the initial choice of their set of variables and they are subject to collinearity biases (Jones *et al.* 2007). In most studies, this usually results in a panel ranging from less than ten to more than fifty variables that are processed through aggregate models and weighting schemes. However, it is worth noting that some of these variables may have an ambiguous role concerning vulnerability. It may thus seem misleading just to add them or to attribute them an universal weight for every local situation on the terrain. For example, a high density of medical establishments and services is either prone to reinforce local vulnerability, if the facilities are destroyed or dysfunctional, or to reduce local vulnerability, ensuring a quick access to medical assistance to the local population. Likewise, density can be seen as a proxy of the reinforcement of local vulnerability due to the concentration of people, homes and infrastructure at risk, or as the indicator of a local reduction of vulnerability because it is usually associated with the concentration of the means of intervention and with the local capacity to effectively respond to and recover from an event. More broadly, aggregate models and weighting schemes suggest that vulnerability subcomponents might be substitutable in some way (Barnett *et al.* 2008). However, the vulnerability of any given place is not necessarily the sum or the product of isolated and permutable characteristics and processes, and the vulnerability arising from poor building resistance or from special evacuation needs is clearly not the same.

The assessment of vulnerability has thus to reveal, not to bury, the particularities of local situations and to focus on the convergence of different vulnerability characteristics in the same place, the interactions between vulnerability dimensions, and with multi-hazard exposure, in order to discuss whether or not they might converge to reinforce (or to reduce) local vulnerability. The relative vulnerability analysis we propose is free from aggregation and avoids the temptation of adding together all available indicators. On the contrary, it underlines the heterogeneity of vulnerability. It is not enough to point out the most vulnerable places; this approach can guide risk reduction decision making by allowing to target precisely mitigation measures to the actual situation in each neighbourhood, i.e. prioritizing structural mitigation in

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the most physically vulnerable places, reducing spatial inequities in the most socially vulnerable neighborhoods, etc.

Method

We propose a first attempt to assess relative vulnerability. The spectroscopy of urban vulnerability does not aim to measure absolute levels of vulnerability, it is rather revealing the heterogeneity of vulnerability by focusing the locally convergent specific characteristics and processes impacting vulnerability in order to inform the implementation of more targeted mitigation policies. This is a two step approach, first focusing on the vulnerability underlying drivers and establishing vulnerability profiles through a factor analysis (PCA) and a clustering method (HAC); and then the second step is to make use of GIS to focus on their spatial distribution in order to confront each vulnerability profile to its multi-threat exposure. In order to answer risk management and mitigation decision making needs, we are alternating a global and analytical view and using the smallest census tracks available level as the main analysis scale.

There is currently a tradition of research focused on the underlying drivers that increase or decrease the impacts of hazardous events on the local population (Adger *et al.* 2004; Birkmann 2006; Blaikie *et al.* 1994; Cannon 1994; Cardona 2005; Comfort *et al.* 2010; Cutter 1996; Cutter *et al.* 2003; Eakin *et al.* 2006; Jones *et al.* 2007; Kaly *et al.* 2004; King 2001; Kreimer 2003; Linkov *et al.* 2004; Mileti 1999; Mitchell 1999; Morrow 2008; OECD 2003; Rashed *et al.* 2003; Schmitt-Thomé 2006; Turner *et al.* 2003; Villa *et al.* 2002; Wilches-Chaux 1998; Wisner *et al.* 2004). Concerning physical (or biophysical) vulnerability, the characteristics most often found in the literature include the resistance of the buildings, informal housing, mobile homes, the absence of housing facilities and the presence of hazardous cooking or heating installations. In social vulnerability analyses, some indicators appear repeatedly, mainly density, special needs populations, age, socio-economic status, unemployment and training. Other indicators are also used, such as critical infrastructures (hospitals) and networks (transportation), facilities concentrating people and that may have special evacuation needs (schools, stadiums, malls, etc.). They can be seen as valuable proxies of functional vulnerability, since the dysfunction or destruction of these facilities worsens any crisis and hinders reconstruction. However, selecting a couple of variables does not adequately capture local vulnerability. It is often the intersection of, for example, poor building resistance, lack of housing facilities, poverty, lack of training and special evacuation needs that impacts the local reinforcement of vulnerability.

We started our analysis with the indicators most in use in the literature, around fifty for each case study. Because of data collection and availability, we had not precisely the same data set in both case studies. However, we reduced the number of variables in order to ensure statistical power (one case study has only 150 spatial units), to avoid collinearity and also to keep a balance between the three dimensions of vulnerability, by picking only around five variables for each dimension (physical, social and functional vulnerability). This reduction and balance of

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various types of indicators linked to people, housing and facilities is attained by analyzing correlations within each one of these three types of indicators, with the variable reflecting the broader situation being selected as the most relevant proxy. Zero-order correlation matrixes were computed for each type of indicator in both case studies. The variables most linearly correlated to the others and less correlated between them were selected as the better proxies of the local convergence of multiple underlying vulnerability factors. For example, long-term unemployment was positively correlated to poverty and lower socio-economic status, and negatively correlated to wealth and higher status; it was thus selected as the best proxy of socio-economic polarization. Conversely, if too many variables were reflecting residential segregation, this process could be overestimated in the vulnerability assessment. In the end, we used almost exactly the same set of variables, around five variables for each of the three vulnerability dimensions, except for the proportion of disabled persons which was not available for Bucharest. The next step was to take under consideration the broader spatial and historical context in order to preserve local specificities, and it introduced two other slight differences. Apart from informal homes and deteriorated high rise buildings, the physical resistance of the urban fabric is pretty much the same in Lyon given the quite homogeneous housing conditions and building standards. Conversely, Bucharest's exposure to earthquakes results in physical vulnerability being of particular concern; we chose thus to use two more variables to evaluate it in this later case. Likewise, Bucharest is a capital city unlike Lyon, this makes functional vulnerability critical because it can easily spread the crisis from local to national level, and we chose as a result two more variables to assess it. However, these slight differences are arising from the broader spatial and historical context, not from the method, which is concurrent with our focus on relative vulnerability assessment. This does not flout the fact that our method does not rely on additive algorithms or on weighting schemes. Furthermore, because the data are not aggregated, scaled or multiplied, our processing are less dependent on the choice of the variables. Anyhow, the variables were selected to reflect broader situations and their adaptation to the context also helps to reveal the specificities of the construction of vulnerability in each neighbourhood for both case studies. Besides, the aim is not to measure vulnerability levels, but to understand the reasons why some places and populations are vulnerable, and thus to inform mitigation policies.

Following our two step approach, first focusing on vulnerability profiles and then confronting their spatial distribution to multi-hazard exposure, we are proposing a two step method. First we focus on the local creation and reinforcement of vulnerability and establish vulnerability profiles through a factor analysis (PCA) and a clustering method (HAC). Then, we make use of GIS to focus on the spatial distribution of each vulnerability profile and to confront them to various hazards and sources of danger. This release from the obstacles encountered in the search for thresholds, rising from the standardization, weighting and aggregation of the various variables. It is possible to retain a balance between a limited number of indicators in order to make sure statistical power by focusing on their interactions. During analysis, interactions, whether positive (such as social marginality and precarious housing) or negative

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(such as populations with special needs and medical coverage), become apparent. The spectroscopy of vulnerability starts with a Principal Component Analysis (PCA). Because PCA is sensitive to the values of the input variables, the raw data is transformed into proportions, so that all variables have the same magnitude: the variables on people and housing are expressed in rates of population and households within each census track, the variables on infrastructures and facilities are expressed in ratio of their capacity or frequentation to the total value for the whole metropolitan area. The coordinates of all census tracks on the factorial axes are then being used as a distance matrix for the Hierarchical Ascendant Classification (HAC). This is a non-spatial hierarchical divisive clustering according to Ward's method, without any weighting. The resulting groups are compact, as homogeneous as possible (low within-variability) and as different as possible one from the other (high between-variability). At each stage, the groups' inertia is used as the Ward level index of the node on the dendrogram. The optimal partitioning of the dendrogram is determined without any strong *a priori* expectations. The larger thresholds in the histogram of level indexes allow to find the right number of clusters. The choice of the optimal partitioning can be justified on statistical grounds by balancing the number of defined groups with the proportion of explained inertia criterion. This combination of factorial analysis and clustering methods makes it possible to eliminate random fluctuations and to obtain more stable partitioning and compact groups.

The results are the vulnerability profiles; they are presented graphically. We call spectra the graphs showing the deviation from average situation for all variables for each resulting group. We interpret those graphs as a sign of the vulnerability profiles emerging from the clustering. These graphs reveal the main positive and negative correlations within each group. On one hand, these graphs present the indicators connected within each profile and, on the other hand, which variables are overrepresented (considerably greater than the average) or underrepresented (below the average). We therefore have a spectrum of each vulnerability profile to compare with the average situations in the urban area being studied. They are the basis for the understanding of the interactions mitigating or reinforcing vulnerability within each vulnerability profile. It is worth noting that it is the original raw data for each profile that is discussed, and not a weighted combination, a scored indice or an aggregated index. Then, we make use of GIS to analyze the spatial distribution of these vulnerability profiles and to confront them to multi-threats exposure.

The use of GIS permits the geocoding of the infrastructures and facilities and the smoothing of heterogeneous data into the smallest census tracks available level. For the more infrequent and less concentrated hazards (such as severe storm or nuclear power plants accidents) we assumed that the hazard zone encompassed the entire metropolitan area in both case studies. On the other hand, spatially concentrated hazards required the delineation of those areas potentially affected. In the absence of better data we made use of the official hazard maps produced in risk management and planning purposes. We also assessed evidence of spatial clustering of the vulnerability profiles using the global Moran's I and Geary's C statistics.

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Finally, we measured the spatial overlay of each vulnerability profile with different hazards delineations in order to discuss their spatial distribution. This all-hazard integrative approach renders “the invisible visible”, it reveals the specific local interactions impacting vulnerability in order to inform risk management policies and spatializes the strengthening or mitigation of vulnerability, thus allowing comparisons to be made.

Lyon: shifting focus from the most exposed to the most vulnerable areas

Lyon, located on the confluence of the Saône and Rhône rivers, is France’s second largest urban area with over 1.2 million inhabitants. Since its Roman occupation, the city center has been located between two hills and remained a major communications hub. In the 20th century, textile manufacturing gave way to the chemical, pharmaceutical and automobile industries which were structured around the port giving onto the River Rhône (Bonnevillie 1997). Lyon is the second largest business and services centre in France as well as being an important tourist destination (Authier *et al.* 2010). Historically, the city has been exposed to several recurrent hazards. The worst disasters to have taken place in the previous century were two landslides in the city center that occurred in 1930 and 1932 (killing 70 people and leaving over 1,000 injured), the expanding vapour explosion at the Feyzin refinery in 1966 and the transport accident that took place in the river port in 1990, resulting in a fire that released a cloud of toxic chlorine gas. This urban area is now exposed to floods, landslides, industrial accidents and hazardous materials transport, as well as to biological hazards resulting from the presence of a laboratory with a level four biosafety rating located near the city centre, and nuclear hazards due to the presence of three nuclear power plants at distances ranging from 30 to 50 km around the city. This complex exposure is at its highest along the River Rhône to the south of Lyon where almost all hazards are present in the city’s chemical and pharmaceutical industrial hub (Rufat 2005).

The recent reinforcements to risk management applied by French legislation following the passing of the “Bachelot law” in 2003 have resulted in approaches solely based on hazard exposure penalizing the population. The obligation to move facilities and public services away from the most exposed neighbourhoods adds to the nuisances caused by the sources of danger and may result in the development having taken place until now in southern Lyon being limited in the future. This has led to the incorporation of vulnerability analysis in the political arbitrations taking place to determine whether to move facilities to different locations, expropriate inhabitants and/or place hazardous materials and activities outside the city. The use of urban vulnerability spectroscopy results in the focus of risk management being shifted from the most exposed areas, overrated by legislation, to the most vulnerable areas.

Vulnerability assessments are conducted on the level of the census tracks for the 72 districts forming the greater Lyons urban area. This represents 528 spatial units. The first step is to identify the major effects of disasters and accidents that could occur in Lyons. These can be subdivided into two categories: instantaneous phenomenon that can damage infrastructure and injure people (such as landslides, overpressure, etc), and slow-growing phenomenon requiring

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the evacuation and/or confinement of inhabitants in the exposed area (such as rising flood waters, spreading toxic cloud, etc). Most of the vulnerability indicators (density, age, income, housing, etc.) are covered by the census, for our purposes we have used the last full census available for Lyon (1999). We also implemented infrastructures and public services through a specific survey and constructed a specialized database with over fifty vulnerability indicators covering the 528 Lyon census tracks.

	Management	Professionals	Technicians	Civil servants and employees	Self-employed	Skilled workers	Unskilled workers	Per capita income
Management	1							
Professionals	0.88	1						
Technicians	0.32	0.59	1					
Civil servants and employees	-0.49	0.06	0.35	1				
Self-employed	0.21	-0.87	-0.28	0.06	1			
Skilled workers	-0.77	-0.89	-0.46	0.11	0.77	1		
Unskilled workers	-0.84	-0.95	-0.61	-0.17	0.66	0.61	1	
Per capita income	0.49	0.59	0.32	0.05	-0.38	-0.81	-0.64	1
Long-term unemployment	-0.69	-0.53	-0.49	-0.04	0.52	0.65	0.80	-0.84

Figure 1. Statistical correlations between socioeconomic indicators in Lyon (1999 census).

We thus performed the reduction and balance of indicators through zero-order correlations matrix. For example, the best indicator of socioeconomic polarization in Lyon is the proportion of long-term unemployed people revealed by the 1999 census (figure 1). Thirteen indicators were taken into account, with six related to population (density, proportion of children, elderly, disabled, long-term unemployed and people without training), two related to housing (proportion of informal and mobile homes, deteriorated high rise housing), and five related to facilities and public services (grouped into five types according to times and levels of use: medical, sports, cultural, educational infrastructures and administration, transport stations and malls). Finally, using density as an explanatory variable leads to results especially marked by a center-periphery gradient, deforming thus the vulnerability assessment. Conversely, using density solely as an illustrative variable allowed underlying correlations to emerge. Due to its ambiguous role in increasing vulnerability and concentrating the means of intervention, density is therefore only used as an illustrative variable.

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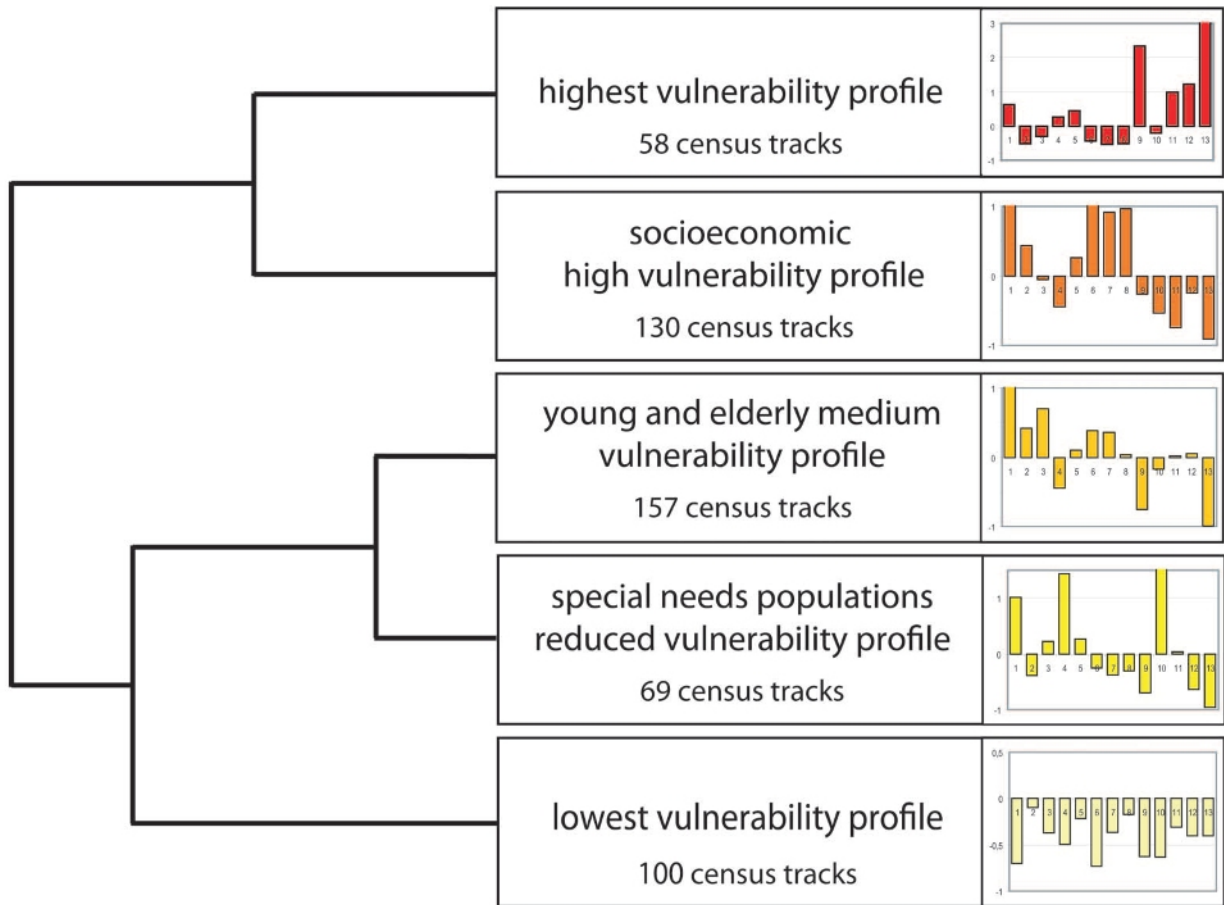


Figure 2: Dendrogram of the clustering of vulnerability indicators in Lyon.

The HAC of these twelve indicators, with density providing an illustrative variable, results in a clustering of the vulnerability profiles in Lyon (figure 2). The optimal partitioning explains 67% of the inertia and defines five groups within the census tracks¹ (figure 3):

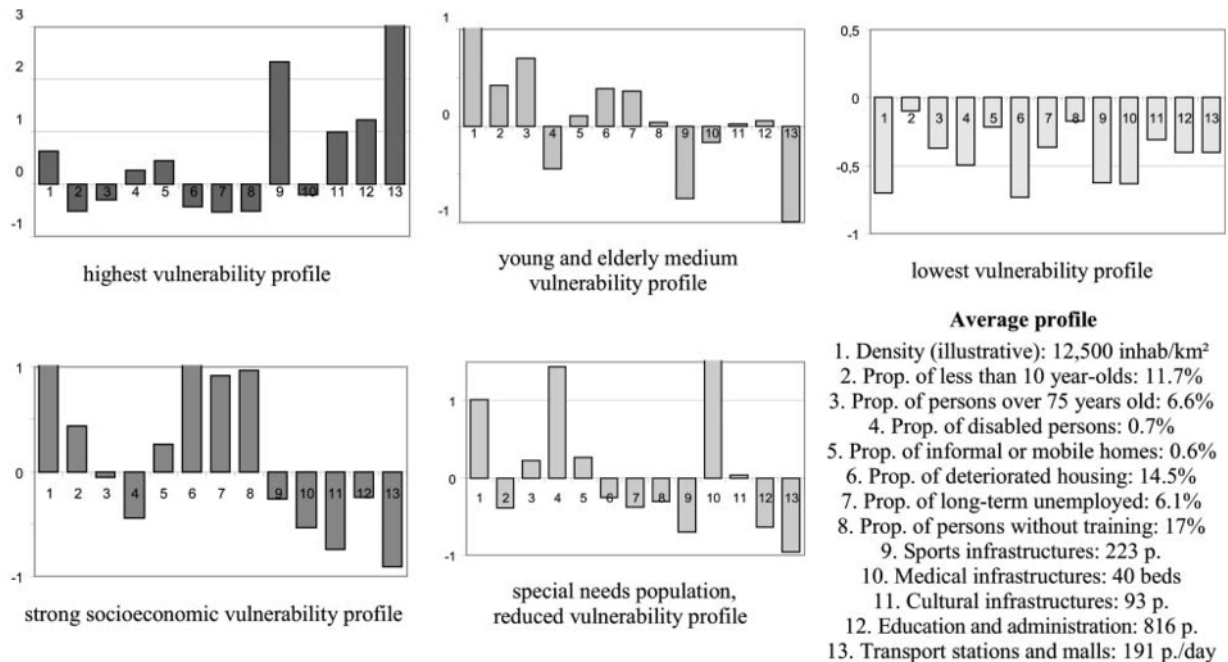


Figure 3: Spectra of the five vulnerability profiles in Lyon.

- Highest vulnerability profile (58 census tracks): this group reveals the connection between the concentration of most facilities and public services (from one to over three times the average), a reduced mobility population (disabled and elderly) and a population living in informal or mobile homes. The positive interaction between these vulnerable infrastructures and populations is increased by a lack of a proper medical coverage. Consequently, this class is defined as having the highest vulnerability profile. This profile picks out the most vulnerable parts of the urban area and its dispersion (Moran's $I = -0.02$; Geary's $C = 1.16$) also reflects the choice of concentrating facilities in a limited number of locations (figure 4).

- Strong socioeconomic vulnerability profile (130 census tracks): this group shows the connection between a young and more vulnerable population and most of the indicators used to reveal socioeconomic vulnerability (informal housing, deteriorated high rise housing, long-term unemployment, and lack of training and education). This profile reveals a strong convergence of vulnerability drivers and the lack of mitigation feedback resulting from substandard facilities and public service coverage. The positive spatial autocorrelation of this profile ($I = 0.40$; $C = 0.52$) reveals the socioeconomic polarization of the urban area, with a concentration of socially vulnerable people and industrial zones in eastern and southern Lyon (figure 4).

- Young and elderly medium vulnerability profile (157 census tracks): this group shows the same connection between a young population and socioeconomic vulnerability indicators as it does with the elderly. However, the local convergence is less concerning than in the previous profile because this group presents a better facilities and public service coverage, even though it lacks public transport and commercial infrastructures. As a result, this group is defined as average

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vulnerability profile. The positive spatial autocorrelation of this profile ($I = 0.38$; $C = 0.64$) reveals a homogeneous group in the city centre and in western Lyon, being quite the opposite of the previous profile. This suggests that the spatial polarization of Lyon is also driven by age (figure 4).

- Special needs populations, reduced vulnerability profile (69 census tracks): this group reveals the local convergence of special needs populations and better medical coverage. This means that reduced mobility persons live in neighbourhoods with greater medical facilities and staff. To a lesser degree, this is also the case of the elderly and those living in informal or mobile homes. In this case, their special needs might well be taken into account. This strong negative interaction is why this class is defined as having a reduced vulnerability profile. The dispersion of this profile ($I = 0.08$; $C = 0.97$) reflects the distribution of the medical infrastructure (figure 4).

- Lowest vulnerability profile (100 census tracks): this last group brings together all census tracks with below average values for the youngest population and considerably lower averages for other variables, including that of density. The positive spatial autocorrelation ($I = 0.45$; $C = 0.52$) reveals the clustering of the lowest vulnerable areas in the urban fabric which are mostly located on the outskirts as well as in the city centre (figure4).

- Finally, the 14 census tracks with less than thirty houses (main residences) in the 1999 census are excluded from the analysis given their statistical irrelevance.

These results reveal the value of simply using density as an illustrative variable. Even though the lowest vulnerability profile also has the lowest density in Lyon, all other profiles share approximately the same density. Furthermore, with the exception of this lower profile, the group with the lowest density has been defined as having the more concerning vulnerability profile. This is due to the strong local convergence of connected vulnerability indicators. It is worth noting that partially taking density out of the vulnerability assessment is the only way to highlight these connections and carry out an in-depth vulnerability analysis.

The use of a GIS also permits to measure the overlapping of the vulnerability profiles with the hazard delineations, such as industrial hazards² (figure 4). This overlapping provides a direct interpretation of risk at the conjunction of hazard and vulnerability. It reveals that only three of the most vulnerable clusters within the urban area are at risk: the city's secondary Oulins and Givors centers, respectively to the west and the south, and Lyon's main Gerland sports complex next to the river port. As can be seen, very few of the most concerning vulnerability profile areas (4 census tracks, being 9,000 persons) are exposed, and if a disaster were to damage part of the urban area's infrastructure and facilities, their dispersion across the city would provide a considerable level of resilience. In addition, most of the neighbourhoods to be found in areas exposed to industrial hazards are of reduced or low vulnerability profiles (21 out of 35 census tracks, the whole population actually exposed being 115,000). This represents a further element that highlights the fact that the risk level in southern Lyon along the river Rhône is reduced, despite the recent focus of risk management in this area. In any case, the strongest socio-economic vulnerability profiles in southern Lyon are mainly exposed to a single risk

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scenario, being the breaking or leaking of a pipe carrying chlorine across the river Saône. In this particular case, the decision required is easy as it would simply require that the industrial process be relocated or that the pipe be placed underground.

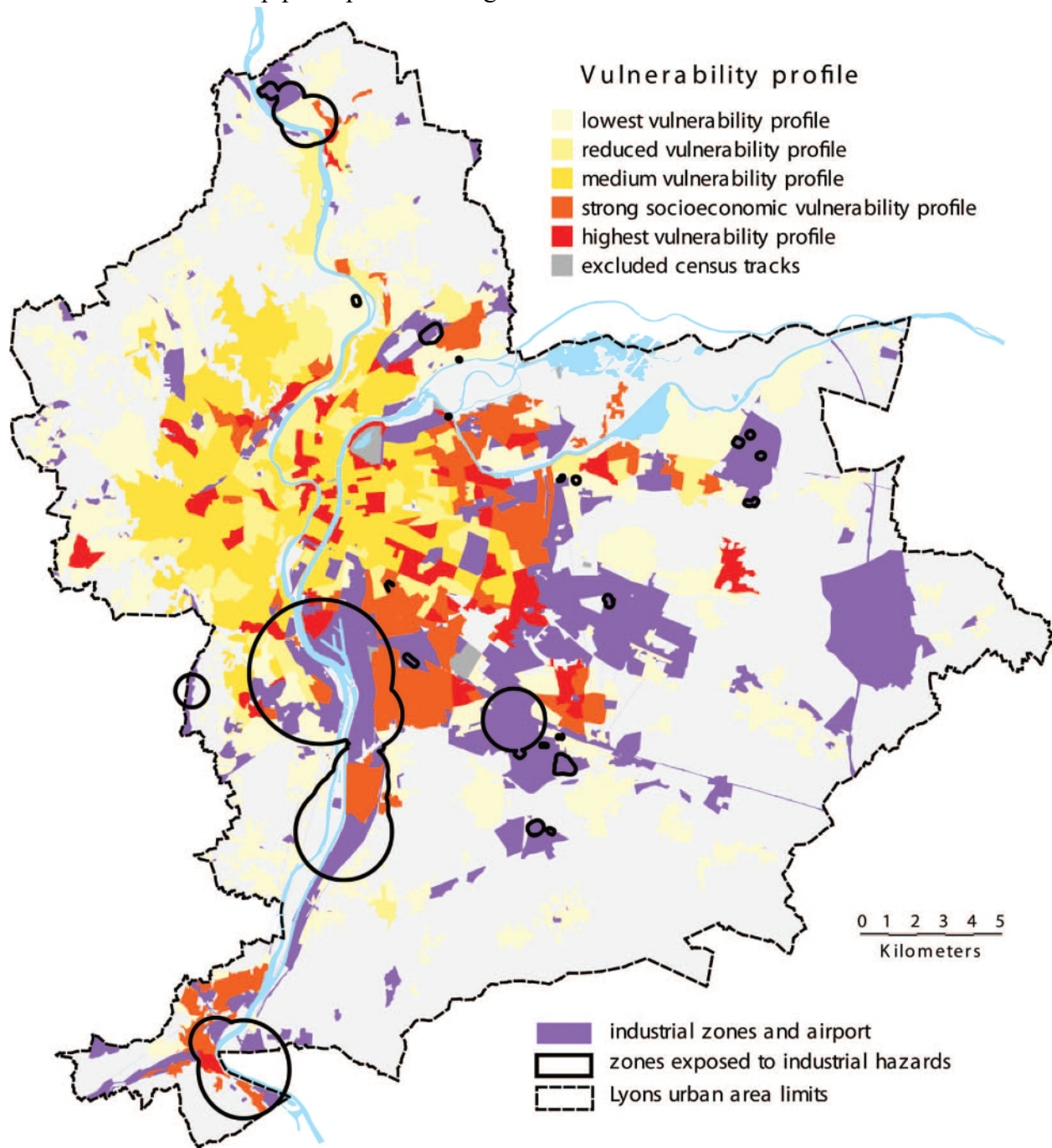


Figure 4: Spectroscopy of urban vulnerability and industrial hazards in Lyon.

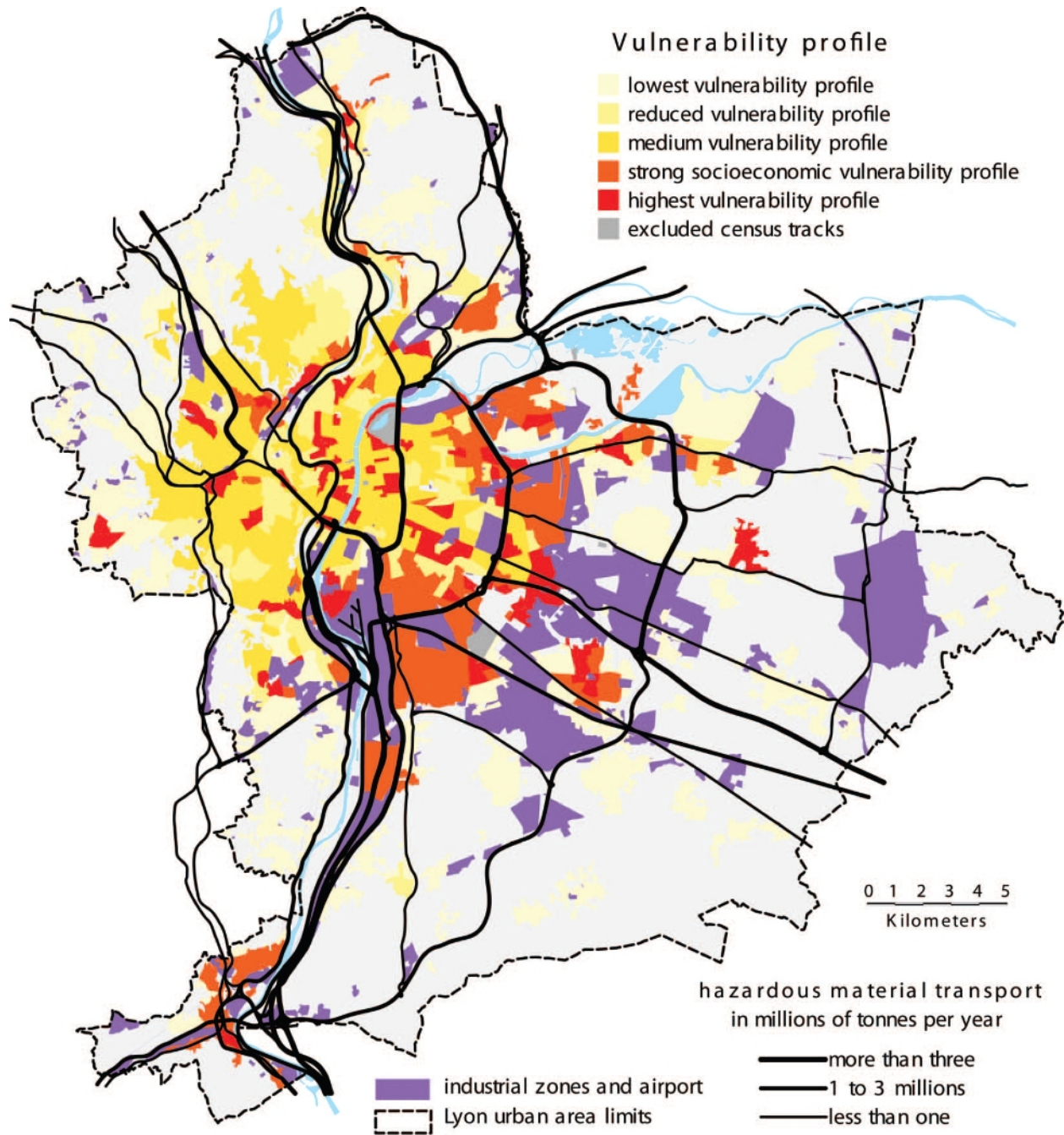


Figure 5: Spectroscopy of urban vulnerability and transport of hazardous materials through Lyon.

The overlapping of the spectroscopy of vulnerability and the transport of hazardous materials through Lyon reveals that 37 out of 57 census tracks (90,000 persons) of the most concerning vulnerability profile are within 100 meters from the routes used (figure 5).

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Regulations concerning the transport of hazardous materials through Lyon only apply spatial and schedule restrictions on road transport despite the fact that hazardous materials are also transported across through the city centre by railway as well as by river. The main railway station in Lyon, located next to the central business district, is used by nuclear fuel and waste convoys, as well as for the transport of highly explosive and toxic materials to chemical and pharmaceutical industrial sites. This situation is far more worrying than the industrial hazards to be found in the southern urban area. For example, an eighteen tonne ISO container on the city's main line tracks could, depending on the duration of the leak and wind speed, generate lethal effects within a 750 to 1,200 meter perimeter (Rufat 2005). As over 150,000 persons, being 10% of Lyon's urban population, live less than 100 meters from routes used for the transport of hazardous material, this type of scenario should be of considerable concern to Lyon's risk management authorities. On the contrary, the "Bachelot law" has resulted in a strategy of prioritizing the reduction of hazardous materials stocks in industrial facilities. This might produce an increase of hazardous material transport across the entire metropolitan area, partly because they are less regulated.

In the case of Lyon, it is worth noting that the spectroscopy of urban vulnerability reveals that this recent mitigation policy is in fact inducing a risk transfer, and what is worse, towards the most vulnerable places of the metropolitan area. As can be seen, while most of the urban area is exposed to hazards (industrial and transport, as well as floods, landslides, etc), only a small proportion is really vulnerable. Consequently, risk reduction appears to be more essential in the most vulnerable places than in the exposed areas. Subsequently, the spectroscopy of urban vulnerability leads to a shift in focus from exposed locations to the most vulnerable locations in Lyon's urban fabric.

Bucharest: revealing the bipolarisation of urban vulnerability

Bucharest, the capital of Romania, has two million inhabitants and is located in the Danube plain near the Black Sea. This small, traditional city, formerly a staging post between northern and western Europe and Istanbul, suffered two radical changes in the last century. Firstly, its famous orchards and convents were destroyed at the end of the 19th century, when Bucharest became the country's capital city, to make place for the construction of palaces and public buildings (Machedon *et al.* 1999). This was followed in the second half of the 20th century by measures taken by the socialist regime to industrialize the city and double its population. The districts to the south of the city centre were demolished to make way for the construction of collective housing and prestigious public buildings (Danta 1993). These radical changes to the city's build environment were justified by recurrent disasters, mainly fires, floods and earthquakes, whose destructive effects often provided pretexts for drastic modernization. The worst disasters over the last century were two major earthquakes that took place in November 1940 and March 1977 (over 7.2 on the Richter scale) and the 1975 spring floods which resulted in the construction of a retention dam just outside the city. Currently, Bucharest is exposed to

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earthquakes, floods, industrial accidents and the dangers of transporting hazardous materials as well as nuclear hazards resulting from the presence of a Chernobyl-like nuclear power plant on the Bulgarian side of the Danube just 200 km away from the city.

The vulnerability assessment was conducted on the level of the census tracks for the six districts forming the capital. This represents 151 spatial units. Like the Lyon case study, we constructed a specific database with around fifty vulnerability indicators, mostly from the last full census available for Bucharest (2002). We also made a collection of infrastructure and public services statistics as well as constructed a GIS, something that had not previously existed in Bucharest. These amenities and services data were smoothed by the grid network used and the totals for each census tracks were integrated with the GIS. Transport and supply networks (drinking water, drainage, electricity, gas) were taken into account through nodes (railway stations, stops, transformers, etc.) and the totals for each district were also integrated within the GIS. Finally, the area covered by the predictable effects of hazards (floods, earthquakes, industrial accidents) was also transferred to the GIS to be mapped.

	Lack of running water	Lack of sewerage	Lack of domestic gas	Lack of electricity	Lack of WC	Open fire installation
Lack of running water	1					
Lack of sewerage	0.99	1				
Lack of domestic gas	0.87	0.87	1			
Lack of electricity	0.62	0.61	0.67	1		
Lack of lavatory	0.93	0.93	0.90	0.62	1	
Open fire installation	0.88	0.88	0.91	0.62	0.94	1

Figure 6: Correlation between the housing supply and facilities indicators in Bucharest (2002 census).

Likewise, we performed the reduction and balance of indicators through zero-order correlations matrix. For example, the proportion of houses without access to running water was chosen as the best indicator for the absence of all network supplies and housing facilities (figure 6). Unlike Lyon, the Romanian capital’s exposure to earthquakes results in physical vulnerability being of particular concern. In Bucharest, the most fragile buildings are those, on the one hand, built from wood and cob (Majuru 2003) and, on the other hand, those built before 1940 which suffered from the last two earthquakes (both registering over 7.2 on the Richter scale) and which basic structure has not subsequently been repaired nor improved (Vossen 2004). Similarly, Bucharest is a capital city unlike Lyon, this makes functional vulnerability critical because it can easily spread the crisis from local to national level, and we chose as a result two more variables to assess it. Finally, similarly to the Lyon case study, density is only used as an illustrative variable.

In the end, fifteen indicators (plus illustrative density) were taken into account: five related to population (density, proportion of children, elderly, long-term unemployment and people without training), four related to housing (wood and cob buildings and buildings build before 1940 and not consolidated, without access to running water and using an open fire

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installation), and seven related to facilities and public services (grouped into types: medical, educational, sports, cultural, institutions and administrations, public transport stations and malls).

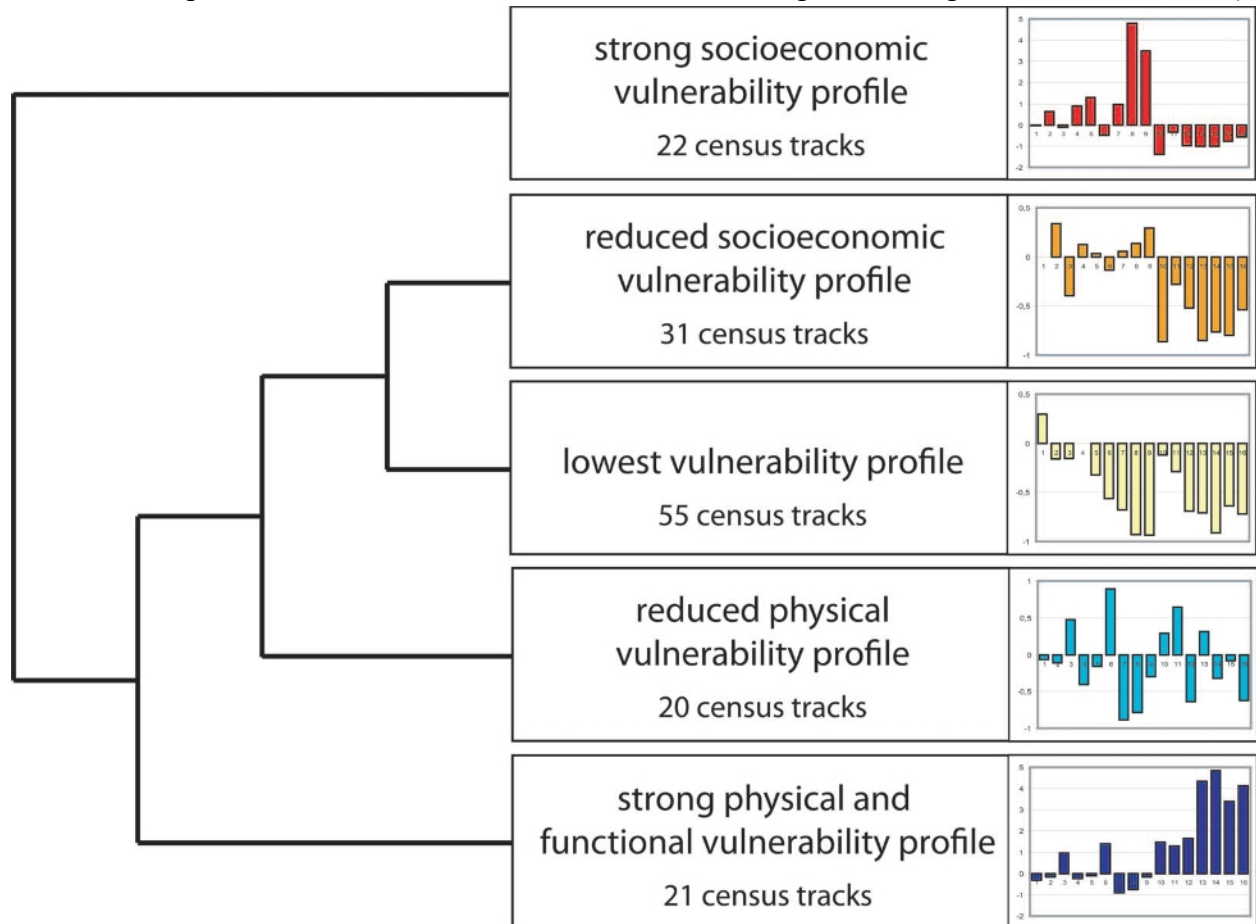


Figure 7: Dendrogram of the clustering of vulnerability indicators in Bucharest.

A HAC of these fifteen indicators (plus illustrative density) results in a clustering of the vulnerability profiles in Bucharest (figure 7). The optimal partitioning explains 68% of the inertia and reveals five profiles within the census tracks³ (figure 8):

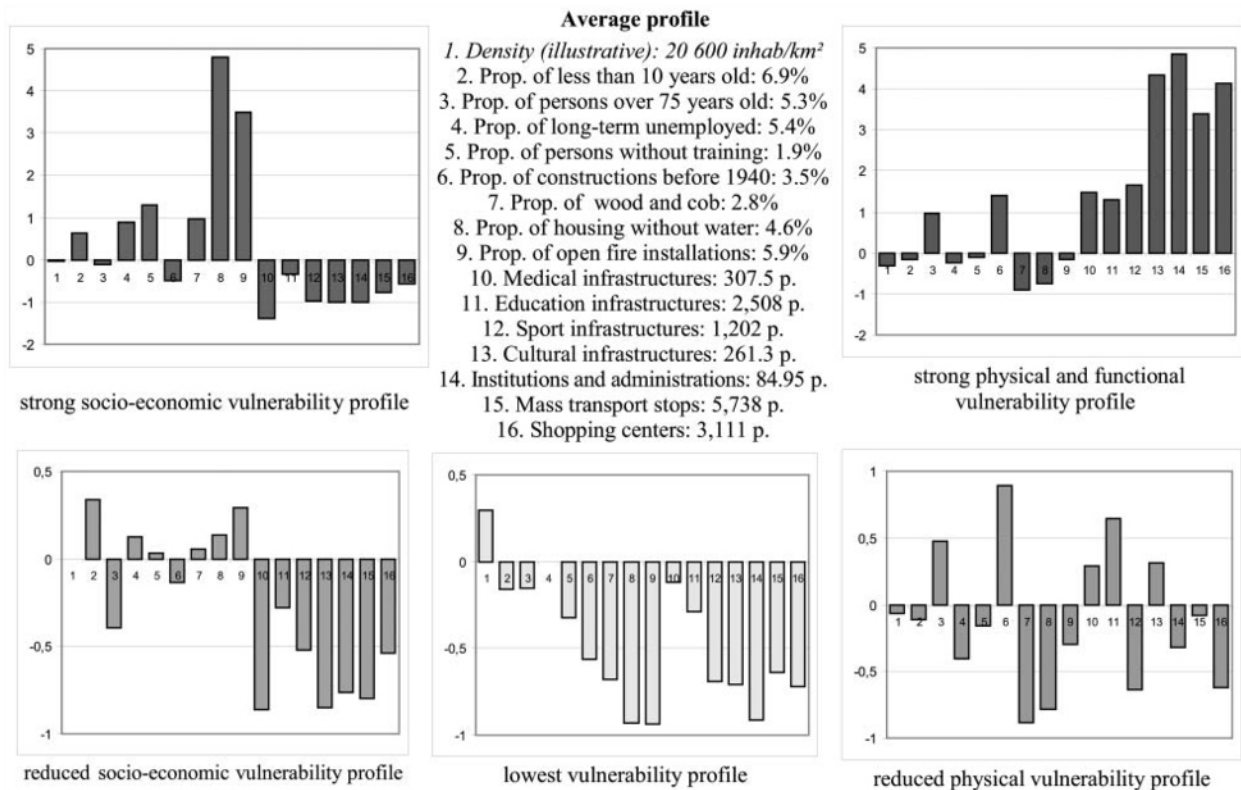


Figure 8: Spectra of the five vulnerability profiles found in Bucharest.

- Strong socio-economic vulnerability profile (22 census tracks): this group reveals the local convergence of the young and more vulnerable population, fragile buildings constructed from wood and cob, and housing with fewer connections and equipment. Socio-economic vulnerability is defined by the combination of persons having not even finished elementary school and those forming part of the long-term unemployed. In addition, these districts do not have the facilities or infrastructure cover that could limit the impacts of crises. These statistical correlations are meaningful given that what we have is the overlapping of a vulnerable population living in fragile and poorly equipped housing that is not connected to supply networks. This situation increases the vulnerability of the population to all types of crises. The spatial autocorrelation of this particular profile ($I = 0.79$; $C = 0.64$) highlights the local convergence of vulnerability in the outskirts of the capital (figure 9). It matches the self-build neighbourhoods that emerged at the same time as the socialist government's industrialization program implemented from the 1950s to 1970s (Mihailescu 2003).
- Reduced socio-economic vulnerability profile (31 census tracks): this group also translates the connection between the young population and economic vulnerability factors. However, in this profile, the connection is less obvious and these districts are equipped with educational infrastructures. This profile refers to neighbourhoods where socio-economic vulnerability is less worrying. It partly fits in with the former self-construction neighbourhoods ($I = 0.20$; $C =$

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0.96) dating back to the period between the two World Wars where the informal housing was partially replaced by the socialist housing blocks of the 1960s (figure 9).

- Lowest vulnerability profile (52 census tracks): this group gathers the districts in which all variables are substantially lower than average, with the exception of density which is used as an illustrative variable. The profile's spatial concentration ($I = 0.24$; $C = 0.74$) reveals that the large socialist government's collective housing blocks, built on the outskirts of the city in the 1960s and 1970s on virgin sites that had formerly been fields and swamps (Mihailescu 2003), appear to be the least vulnerable neighbourhoods (figure 9).
- Reduced physical vulnerability profile (22 census tracks): this group confirms the convergence of the older population and buildings damaged by earthquakes (built before 1940). However, this profile also reveals a connection between the older population and medical, educational and cultural infrastructures. This can be seen, for instance, by the fact that medical coverage is a mitigating factor for the population living in these districts. This is why this group is defined as having a reduced physical vulnerability profile. This profile is almost randomly disseminated ($I = 0.08$; $C = 0.70$), it is to be found to the south of the city centre, in areas where the socialist government's radical demolition programs were implemented during the 1980s (Danta 1993), as well as in the city centre outskirts where the existing urban fabric had been partially replaced by the socialist government's collective housing and public buildings during the 1960s and 1970s (figure 9).
- Strong physical and functional vulnerability profile (22 census tracks): this group gathers the central census tracks, where the connection between the older population and buildings damaged by earthquakes is strongest, and which concentrates infrastructures, political institutions, administrations, facilities and the main network intersections. This group highlights thus the convergence of a strong functional vulnerability and the concentration of an older population living in fragile buildings. The spatial autocorrelation of this profile ($I = 0.35$; $C = 0.17$) reveals a homogenous group that runs from the downtown centre to the north-west of the city (figure 9). This is the historical center of Bucharest, characterized by old single family home mostly occupied by elderly people who managed to "recover" their houses that had previously been nationalized by the socialist regime. However, these people often do not have the resources to maintain or reinforce their damaged buildings (Cinà 2005; Vossen 2004).
- Finally, the two main university campuses in Bucharest (Grozavești and Agricultură) are excluded from the analysis as they represent extreme values insofar as a large number of indicators are concerned (figure 9).

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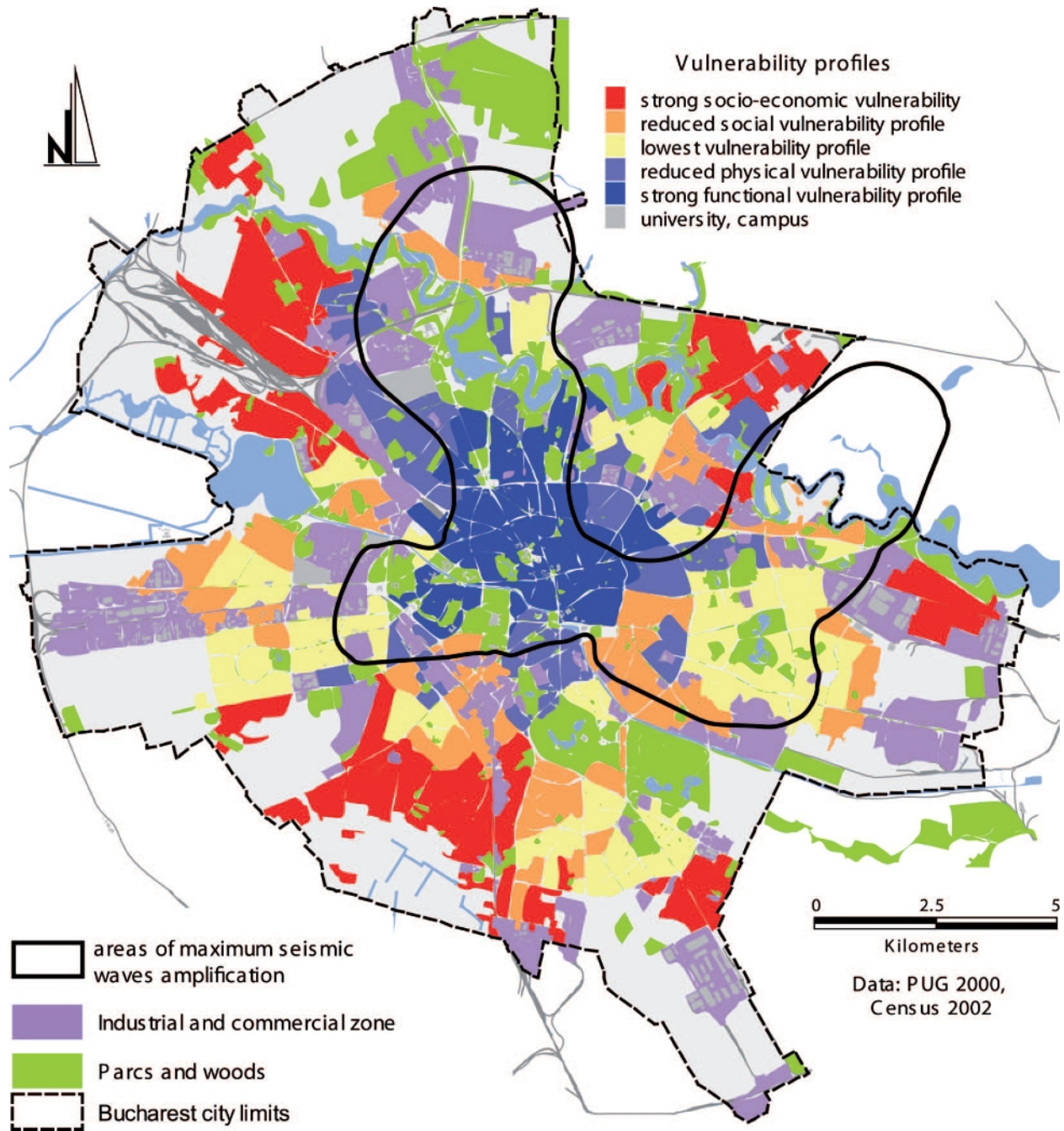


Figure 9: Spectroscopy of urban vulnerability and seismic wave amplification in Bucharest.

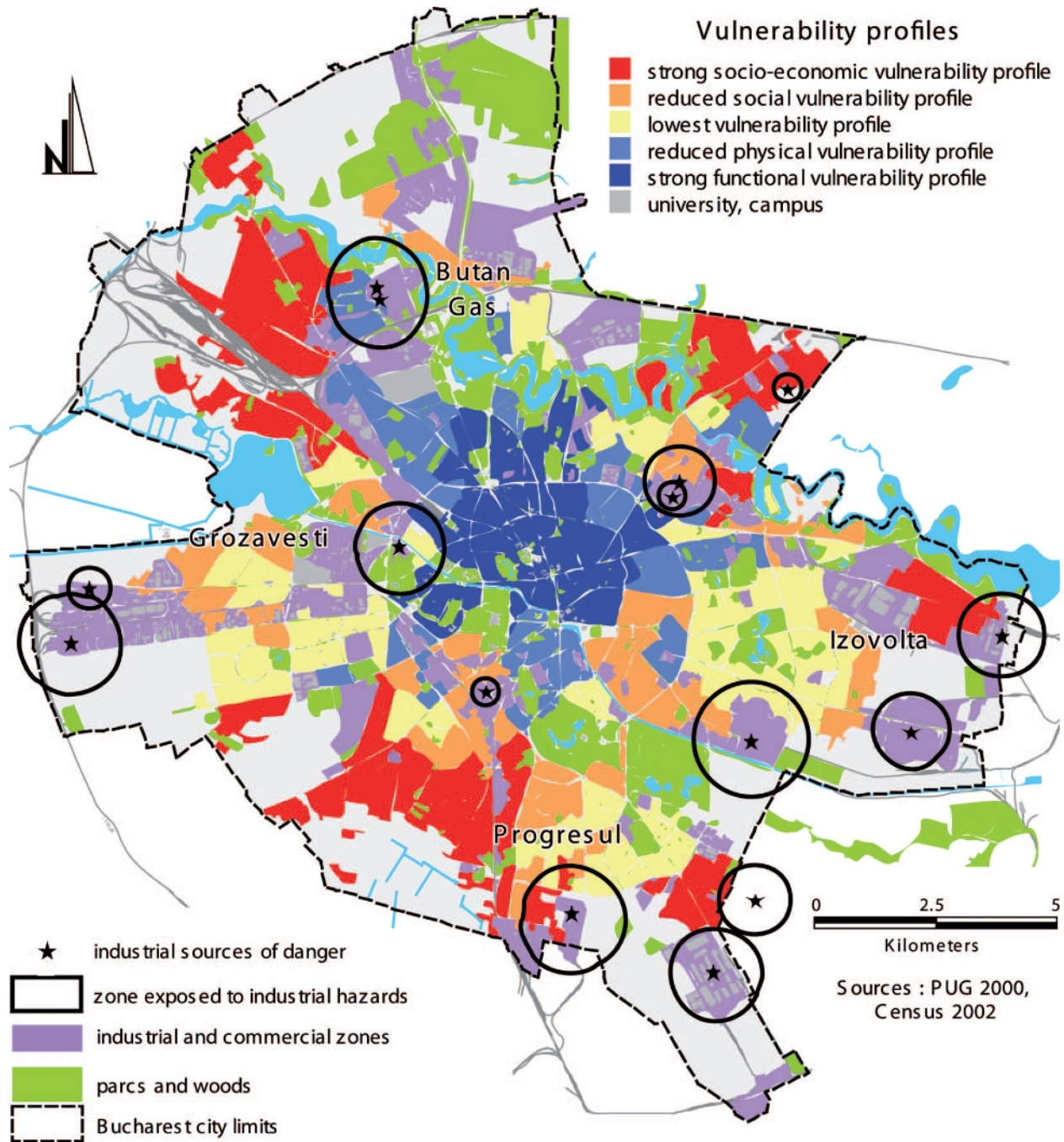


Figure 10: Spectroscopy of urban vulnerability and industrial hazards in Bucharest.

In the case of Bucharest, the value of using density only as an illustrative variable is even more obvious. It allows an in-depth vulnerability analysis that reveals a bipolarization of physical and functional vulnerability in the city centre and socio-economic vulnerability in the outskirts. As

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these various vulnerability dimensions result in dissimilar mitigation measures and priorities, their precise identification and spatialization is critical. In addition, the group with the highest density has also been defined as having the lowest vulnerability profile. This does not mean that these socialist collective housing neighbourhoods are not vulnerable. It should not be forgotten that this spectroscopy of vulnerability is a relative assessment method, and that, consequentially, less vulnerable areas may still be quite vulnerable. In reality, with the exception of medical and educational coverage, collective housing neighbourhoods present under-average facilities and public services. Finally, this relationship between collective housing and mitigation remains surprising. The clue to this, rather than lying in the built environment which was designed to be earthquake resistant, probably lies in the imposed social and age mix. This suggests that the response to vulnerability is more a question of social and spatial cohesion alongside a reduction in disparities, rather than a matter of resilience, being a feature that is not its perfect antonym.

Furthermore, the overlapping of vulnerability and hazards reveals specific interactions between this bipolarization of vulnerability and the neighbourhoods contrasted exposure to the various hazards⁴. For example, 18 out of the 22 census tracks of strong physical vulnerability profile, which are revealing the convergence of an older population and damaged buildings, are also located within the area of maximum seismic wave amplification (figure 9). This overlapping represents 175,000 persons, being 9% of Bucharest's total population. Institutions, infrastructures and strategic interconnections are also concentrated in the same area. This interaction between hazards, urban dynamics, a vulnerable population, major infrastructures and institutions clearly reveals how risk is constructed and vulnerability increased. In the case of an earthquake, these local interactions could result in consequences that could extend over the entire country. This is a major challenge facing both Bucharest and Romania.

What is more, populations confined in self-construction neighbourhoods, representing the strong social vulnerability profile, are also the closest to industrial hazards sources (figure 10). This vulnerability profile associates the presence of fireplaces in houses made from wood and cob with their poor resistance to fires and or floods, being hazards that are able to affect almost any profile. Apart from earthquakes, the most serious potential risks are linked to accidents that might occur on the Butan Gaz platform to the north, the Izovolta chemical manufacturing factory to the east, and the Grozavești and Progresul crude oil power plants. Most industrial hazards could affect neighbourhoods with a strong socio-economic vulnerability profile and a large number of low resistant buildings. However, the most worrying scenario is that of the Grozavești power plant. An accident at this plant, located in the area of maximum seismic wave amplification, would directly expose the presidential palace, the main campus and a major commercial area, as well as the city's most important medical centre. An accident or an earthquake would cause major damage and disorganize national institutions while also destroying the key means of intervention and medical assistance. Bucharest is clearly a city at risk. In this case, the spectroscopy of urban vulnerability provides an understanding of different local interactions that

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reinforce vulnerability and that could be able to expand the consequences of a disaster from a local to a national level.

Conclusion

The spectroscopy of urban vulnerability meets the increasing need to have an all-hazards comparative vulnerability assessment method (Cutter 2003). Drawing on previous results from the place-based approach, we proposed to focus on the local convergence of specific characteristics and processes reinforcing (or reducing) vulnerability in order to inform the implementation of more targeted mitigation policies. We suggest that focusing on the complexity of relative vulnerability and local interactions rather than attempting to quantify an absolute level of weakness or resilience may be a way to overcome most methodological obstacles facing vulnerability assessment. The combination of factor and cluster analyses allowed us to minimize *a priori* expectations and underlying assumptions. Instead, it requires interpretations to emerge from the resulting graphs revealing the specific vulnerability signature of the different groups that we have called spectra of vulnerability. And it forces to make explicit explanations of the complex local interactions impacting risk and vulnerability. This method leads to a readable mapping while transferring the original complex data that has not undergone any transformations. It juxtaposes maps and the vulnerability spectra of the various profiles, and then overlays them on hazards maps. The result is an intuitive and synthetic reading. The Lyon and Bucharest case studies reveal two very distinct historical and cultural backgrounds, the specificities of local situations in the face of the various hazards and interactions between hazards, urban dynamics and vulnerability. The two cities also permit local multi-threat comparisons as well as international comparisons by shifting focus from vulnerability metrics to the identification of specific local interrelated processes and characteristics impacting vulnerability.

However, this assessment method also calls for certain number of comments. While it answers mitigation and decision-making needs, the multiplication of information makes the overlaid mapping a complicated task. Although the hazards have been analyzed one by one, climatic, biological and nuclear hazards have not been taken into account. Besides, we made use of the official hazard exposure maps produced in risk management and planning purposes. It is worth noticing that all these delineations are deterministic rather than probabilistic. However, they face the classical issue that drawing the lines defining the scope of potential disasters does not prevent disasters to occur outside the area. Those hazards maps tend to be arbitrary and making use of them often masks the negotiation process underlying their production and adoption. Nevertheless, hazard zonation mapping is necessary for the proper risk management policies and those delineations are still the only available reliable data. In addition, this method is partially subject to arbitrary decisions in the delineation of the census tracks despite the fact that the clustering permits the identification of coherent groups that extend beyond grids. While a smoothing algorithm would overcome these difficulties, it would also eliminate the census tracks

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necessary to inform risk management policies. Another limitation lies in the decision to give the choice of abode (main residence) as the frame of reference. If places of work had simultaneously been taken into consideration, this would have led to a proportion of the population being counted twice. Consequently, this method only indirectly examines the vulnerability of activities and networks. These are treated by the functional dimension of vulnerability, but in connection with the place of residence. Finally, non-built spaces are deemed to be uniform and their specific vulnerability is never taken into account.

The spectroscopy of urban vulnerability can still be improved, especially through the use of remote sensing aimed at extending the analysis to all types of spaces and agglomerations. In addition, improved accounts of activities, networks and flows would be valuable. Once further developed, this method could be extended from urban to extra-urban analysis and become a multi-scale vulnerability assessment method. However, more case studies would be needed to develop the method's local and international comparison possibilities.

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¹ In the case of Lyon, the optimal partitioning defined 5 (67% of explained inertia), 9 (71%) and 11 groups (75%). We selected the 5 defined groups partitioning as the following stages did not powerfully increase the amount of explained inertia. The further divisions tended to isolate very small clusters on the grounds of acute values for one single variable.

² In the case of Lyon, in the absence of better data, we made use of the official hazard delineation approved by the local authorities in August 2004 in application of the European Seveso directive (2003/105/CE).

³ In the case of Bucharest, the optimal partitioning defined 3 (49% of explained inertia), 5 (68%) and 9 groups (73%). We selected the 5 defined groups partitioning because the first partitioning only explained a slight amount of the total inertia and the last partitioning did not supply a consequent increase of the amount of explained inertia.

⁴ In the case of Bucharest, we also made use of the official hazard maps produced in risk management and planning purposes. We also used the industrial hazard zoning approved by the local authorities in September 2008 in application of the Seveso directive and the seismic wave amplification microzonation released by the Romanian National Institute for Earth Physics (INFP) in September 2006. It is worth noticing that all these delineations are deterministic rather than probabilistic.