Flood risk management centred on clusters of territorial vulnerability

Florent Renard

UMR 5600 CNRS Environment City Society, Université Jean Moulin Lyon 3, Lyon, France

ABSTRACT
Traditionally, risk management has been focused on the control of hazards. However, this field of research is now more aimed at reducing vulnerability. Methodology for gaining accurate knowledge of territorial vulnerability is proposed here. It is available for all types of hazard and applicable to any territory. It is based on a census of elements at risk and uses expert weighting to define vulnerability, relying on semi-structured interviews with local stakeholders. Finally, spatial statistics are used to highlight key areas of a town with clusters of higher vulnerability. This method is applied in this article to Greater Lyon urban area, in France.

1. Introduction
The area covered by Greater Lyon in the northern part of the Rhone Valley has a population of 1.3 million (Figure 1). It is particularly exposed to several types of hazard with various causes. First of all, technological hazards are involved because of the large number of petrochemical facilities in the ‘chemical corridor’ south of Greater Lyon. Most of these have risk classification (Seveso II). As a result, large amounts of dangerous materials are transported by road, rail or river and transit via the entire urban area. There is also a nuclear risk, with three power stations within 30–50 km of the city centre, and a biological risk as the Jean Mérieux laboratory with P4 security (the highest security level in France) is in the south of Lyon (7th district). However, the most worrying hazards have natural causes: a geological risk (land movements or slips) and above all those resulting from water. Flooding is the most frequent and costly risk in Greater Lyon (Renard 2010), as in most of the rest of the world (UNISDR 2011; Jongman et al. 2014). It can be caused by the Rhône or the Saône, the two main watercourses in Greater Lyon; the kinetics is slow but operates on a very large scale. Torrential flash floods (Marchi et al. 2010; Tarolli et al. 2012) can also occur in the whole of the western part of the area as it is crossed by numerous streams with steep gradients and that run into the Rhône (Figure 2). Flooding by urban runoff causes many problems in the centre of Greater Lyon and also in the plain in the eastern part of the area where there is no natural stream network and where ground impermeability is high. Finally, flooding is possible in the city centre after heavy rainfall as a result of rises in groundwater. Practically the whole of Greater Lyon is therefore at risk from the submersion of the assets there.

Although numerous focused studies have been made of the hazards (physical phenomena of a given nature, intensity and occurrence) linked to these risks in the Lyon area (Kouyi et al. 2011; Becouze-Lareure 2012), publications on the vulnerability of Greater Lyon are rare. In fact, after being based historically on the control of hazards, risk management has recently addressed...
Figure 1. Location of Greater Lyon in France (top-right), and its topography and hydrology (right).

Figure 2. Step-by-step procedure for a territorial vulnerability clustering process.

1. Census of the elements at risk (human, environmental, and equipment assets)
2. Building of a vulnerability index based on the previously identified assets
3. Asset weighting depending on their vulnerability by local expert judgment
4. Vulnerability functions using matrix calculations from the Analytic Hierarchy Process
5. GIS processing: territorial physical vulnerability mapping
6. Spatial clustering to identify significant concentrations of high vulnerability and outliers
mitigation of the vulnerability of assets. Here, flood risk management methodology is proposed, centred on territorial vulnerability. The study is applied to Greater Lyon but can be transposed to any area. The notion of risk is seen here as the possible occurrence of a hazard for potentially vulnerable assets. These fundamental terms central to this paper are discussed in detail below in the first part of the article, and a comparison is made between the international literature and the French point of view.

The aim of this study is to obtain precise spatial knowledge of the territorial physical vulnerability in the face of floods. This article differs from studies based on the evaluation of social vulnerability (as in Cutter 1996; Cutter et al. 2003; Borden et al. 2007; Holand et al. 2011; Lujala et al. 2014, for example) because it uses a full census of the elements at risk (assets) in the area and a decision aid method, based on the judgement of specialists, is applied to evaluate the different vulnerabilities of these various elements and weight them according to their sensitivity. The results are transcribed in cartographic form by a GIS using geomatic treatments and a fine grid. This practical method designed for operational use, and can be of use to researchers, stakeholders, and local councils, is discussed in the second part. Finally, identification of key sectors is provided, using geostatistical techniques, to study spatial autocorrelation and clusters and outliers, and to offer site-specific lines of research and management for local stakeholders.

2. Reminder of the key elements forming a risk

2.1. Risk – a polysemic notion

Risk is a polysemic notion shared by numerous disciplines and has many definitions (Shi & Zeng 2013; Lummen & Yamada 2014; Marzo et al. 2015). It is generally perceived as the product of interactions between a society and its environment in a given area (Kron 2002; UNISDR 2011; IPCC 2012; Poussin et al. 2012, among others), the probability of a hazard event affecting a population (Mileti 1999; Cutter 2001; Borden et al. 2007), or as the likelihood of occurrence of the hazard and can be attenuated or amplified by good or poor mitigation practices (Cutter 1996). For Armenakis and Nirupama (2013a), risk (R) is the relation between a relative impact of hazard (H) and vulnerability (V): \( R = H \times V \) (Armenakis & Nirupama, 2013a, 2013b).

A close review of the literature in French reveals close similarity with international concepts, especially the last one mentioned above, which will be used in this study. More precisely, Meschinet de Richemond and Reghezza (2010) consider that vulnerability is inherent to the territorial system. It is a composite notion considered as the potential concretization of phenomena that can be forecast to a greater or lesser degree and that are generally negative in space and time (Demoraes & D’Ercole, 2009). It is thus the result of a meeting between a disputing factor of a random nature and a vulnerable element (Chocat 1997) or the probability of loss of assets subjected to an event causing damage: the hazard (Veyret & Reghezza 2006). Bourrelier (2006) held that the ‘risk-vulnerability’ pair is the key to the management of all risks, and Léone (2007) wrote that ‘it is now accepted that risk is the result of a combination of a threat (the hazard) and assets that are more or less vulnerable’.

2.2. Hazard and exposure, long the only factors taken into account

A consensus that a hazard represents a potential threat from an environmental, technological or human process is found in the literature published over the past 20 years (see Mileti 1999; Cutter 2001; Borden et al. 2007), with a significant variation in the choice of hazards themselves: natural, technological, or caused by man. The concept of hazard is accompanied by that of exposure or hazard impact zones (Armenakis & Nirupama 2013a), defined by the IPCC as ‘the presence (location) of people, livelihoods, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected by physical
events and which, thereby, are subject to potential future harm, loss, or damage’ (IPCC 2012). In France, geography was naturalistic for a long time and first devoted to the analysis of hazards before becoming anchored in social sciences (Veyret & Reghezza 2006). Risk management was therefore long focused on mastery of hazard and knowledge of hazard has made considerable progress during the last few decades. Indeed, phenomena have been identified, measured, modelled, reset historically, updated and mapped (Bourrelier 2006). Thus, until the end of the 1980s, the maps of so-called ‘natural’ risk generally had only a topographical base on which were superimposed the zones exposed to flooding or landslides, avalanche corridors, etc. (Demoraes & D’Ercole 2009).

A hazard is perceived as a threatening event that can cause damage and that is characterized by its intensity during a given period and to a given extent and by the probability of its occurrence. Griot and Ayral (2001) see it as a possibility of the occurrence of a phenomenon resulting from factors or processes that escape man, at least in part, and for Propeck-Zimmermann et al. (2009) hazard is understood as being the probability of occurrence of an event that can lead to damaging effects in a given area.

2.3. Vulnerability: recent, necessary awareness

Unlike hazard, the term vulnerability appeared in the literature at a very late date. It can be seen as ‘the susceptibility to harm from the risk posed by hazard events at a particular location’ (Borden et al. 2007), the ‘propensity or predisposition to be adversely affected’ (Lujala et al. 2014) or the ‘fragility or weakness of the unit under consideration, be it a building, a place, a person, a group, or settlements’ (Armenakis & Nirupama 2013a). It is a function of exposure, sensitivity and response (Cutter et al. 2008; Cutter & Finch 2008). Many researchers have seen this concept as one of the keys for managing risk (Cutter 1995; Tobin & Montz 1997; Lujala et al. 2014).

Vulnerability assessments are used to determine the potential loss of life or damage to equipment and environmental assets from extreme natural, technological or social events, and are necessary ‘in proposing hazard reduction alternatives where mitigation normally takes the form of structural (engineered) approaches to hazard reduction’ (Cutter 1996). It replaced appellations as varied as sensitivity, susceptibility and fragility (Veyret & Reghezza 2006), but ‘still means different things to different people’ according to Cutter (1996), who listed about 20 different definitions of vulnerability, and are ‘not salient concerns until after the disaster occurs’ (Cutter et al. 2008). Haziza (2007) sees it as a territorial response to hazard. In the present study, vulnerability is in line with the proposal by Gleyze and Reghezza (2007) that is should be understood as the propensity of a human, equipment, environmental asset, etc. to suffer damage. Any element at risk that would be damaged by the impact of a hazard is therefore considered to be vulnerable. The ambiguousness of the vulnerability concept is shown by the large number of definitions in the literature, each being that of the author concerned. Thus, the definition of vulnerability and its evaluation and mapping is very often an extremely delicate operation.

2.4. Vulnerable assets and elements at risk?

The term ‘asset’ or ‘element’ is also very frequently encountered in the literature on the notion of risk. It has even become practically indissociable from the notion of vulnerability. Indeed, for Borden et al. (2007), ‘the level of vulnerability associated with a place is composed of the social, physical, and built environment characteristics that make a place more susceptible to risks and hazards and influence the ability to recover from them.’ Along with these physical and built environment characteristics, some authors added the natural environment and also anything that can suffer damage or malfunction and refers to the composition and overall functioning of the territory (population, buildings, natural environment, transport, etc.), or all the persons and goods directly threatened by
the hazard and that may suffer prejudice or damage (Griot & Ayral 2001; Propeck-Zimmermann et al. 2009). For Lujala et al. (2014), the key assets consist of buildings, roads, and residential, industrial and agricultural land, and for Rød et al. (2015) they may be buildings, roads or other infrastructure together with agricultural land or other land-use categories. Demoraes and D’Ercole (2009) consider that they form the elements that are essential for the functioning and development of a territory and damage, failure or loss would therefore be particularly prejudicial for it. Various hazards can affect the elements at risk in Greater Lyon and an evaluation of their physical vulnerability is performed below.

2.5. The limits of previous evaluations of physical territorial vulnerability in Greater Lyon

There are many well-known studies on the evaluation of social vulnerability to hazards, mainly from the Hazard and Vulnerability Research Institute of the University of South Carolina (Cutter 1996; Cutter et al. 2003; Borden et al. 2007; Cutter et al. 2008), the Department of Geography of the Norwegian University of Science and Technology (Holand et al. 2011; Rød et al. 2012; Holand & Lujala 2013; Lujala et al. 2014), the Crisis and Risk Research of Mines Paris Tech (Garbolino & Lachtar 2012) and the Flood Hazard Research Centre of Middlesex University (Kuhlicke et al. 2011). Social vulnerability is seen as the ‘sensitivity of a population to natural hazard and its ability to respond to and recover from the impacts of hazards’ (Cutter & Finch 2008). Its evaluation is based on indicators such as socioeconomic status (per capita income, median house value, etc.), gender, race, ethnicity, age (% less than 5 years or greater than 65 years old, etc.), employment and occupation, education, and on built environment indicators such as residential property (median age of housing units, density of housing units, etc.), commercial and industrial development, transport infrastructure (airports, interstate miles, rail miles, etc.) and monument and icons. A factor analytic approach such as principal component analysis with a varimax rotation and Horst normalization is used to reduce the number of independent variables that account for most of the variance and to identify underlying factors that make places socially vulnerable (Holand et al. 2011; Lujala et al. 2014). This leads to establishing a social vulnerability index (SoVI), a built environment vulnerability index (BEVI) or an Exposure Index (EI). In contrast, studies on physical territorial vulnerability based on the quantification of real elements at risk (and not on indicators) in hazard exposure and on a qualification of their innate physical vulnerability are more rare. Most studies are generally limited to addressing residential density. Indeed, the authors agree with Griot (2003) who found that the analysis of about 20 vulnerability studies shows that they often do not take all the vulnerable elements into account. Equipment, and even more frequently environmental assets, is not usually included in these evaluations despite the fact they are in the hazard area and can also be impacted by the disaster. In addition, the unit of analysis is often too coarse: the evaluation of human assets generally consists of a study of the number of residents by state, county or town. Furthermore, the weighting of the vulnerability of the elements at risk is absent in most cases, and only the number of inhabitants is taken into account, and not their personal vulnerability during the disaster, for example their activity (work, study, leisure, transport, etc.) and their physical and social features (age, mobility, qualifications, etc.).

Previous studies on Greater Lyon include these limits (especially Combe 2007; Rufat 2007; Renard & Chapon 2010) and motivated the present work, along with the need for local stakeholders to have precise knowledge of clusters of high territorial vulnerability. This study thus has a more comprehensive approach, includes nearly all the assets in the territory of Greater Lyon and provides quantitative and qualitative methodology for assessing the relative physical vulnerability of an area. In addition, the unit of analysis – a 100 m x 100 m grid – is fine enough to provide local information. However, it should be noted that risk management has long been focused on the mastery of hazards, whatever their site of application or nature, and is in no way a characteristic of the managers of Greater Lyon.
3. Two methodologies for vulnerability analysis and identifying priority zones

3.1. A hierarchic multicriterion decision aid method for the analysis of vulnerability

3.1.1. Many assets and different vulnerability

Greater Lyon has various types of assets at risk. They should be listed in a fairly exhaustive manner to obtain a complete view of the system. Distinction is therefore made between three categories of elements, depending on their nature: human, equipment and environmental. Discrimination is subsequently more detailed. They are affected by hazards in different ways and do not display the same vulnerability to floods. Human assets thus consist of various groups that react in their own way when confronted with a given hazard. Indeed, the age of the population and the degree of mobility are determinant for individual vulnerability, first because the young and the old are more likely to suffer from accidents and have more difficulty in recovering. It is also more difficult to evacuate these categories.

Similarly, the vulnerability of environmental assets differs according to their nature. Farmland is more or less vulnerable according to the suitability of crops (Combe 2007). Vines are thus little suited to submersion, market garden and cash crops are the most fragile and ploughed land is more or less vulnerable to the river constraint according to the type of crop sown (for example, maize withstands submersion better than wheat), prairie is very well suited to frequent submersion. In natural areas such as marshes, woodland and brush zones, water bodies, ponds and lakes, it goes without saying that submersion contributes to the good natural functioning of these wetland environments (Combe 2007). The same mechanisms are seen in equipment assets, for example a transport network that is raised to protect it against overflowing, or at least put it out of the range of the most frequent floods, in order to maintain traffic along the major routes in the urban area (Combe 2007).

The first part of this study thus addresses the evaluation of asset vulnerability. This is examined with regard to the flooding hazard but can obviously be adapted to all types of assets and is one of the perspectives of this work. Here, use is made of decision aid based on multicriterion hierarchical methods and specialists’ opinions. The evaluation must be objective and the conclusions must be shared by the greatest number in order to reach a consensus with a view to operational application.

3.1.2. Choice of a decision aid method: AHP

Methods for aid in decision-making are used to facilitate problems of choice of different alternatives and decisions and evaluation in complex situations involving several qualitative and quantitative criteria. Multicriterion aid has been used here and consists of setting out the alternatives using several criteria addressed: together: the multicriterion approach. The aim here is to award priorities to the different assets according to their vulnerability with regard to a flood risk. A classification procedure is therefore needed. The use of one method rather than another is defined by the main parameters such as the objectives, simplicity of use, the closeness of evaluation, flexibility, the time needed to implement them and the results acquired. Different techniques have been assessed (Renard 2010) and the Analytic Hierarchy Process (AHP – Saaty 1980) has been chosen. This has the advantage of being fairly flexible and adaptable. It is also the only method for retroactive verification of the coherence of all comparisons.

AHP is a theory of measurement of criteria in a given situation, based on the derivation of relative importance priorities using comparisons of pairs of homogeneous alternatives with a common feature (Saaty 1994; Kendrick & Saaty 2007). It draws on the systemic method (focused on the functioning of the whole) and the deductive approach (interrelation between parts) to address a complex situation using different components that can interact with each other in order to quantify them and award relative value to their impacts on the overall system. This component quantification approach is based on experience and the judgement of specialists and leads to the weighting of the different components: functions of vulnerability in this case.
The multicriterion analytic hierarchy process is thus based on the following five main stages:

1. a detailed description of the system and the assets in order to describe, synthesize and break down a complex situation,
2. the construction of hierarchies to organize assets to address the problem; this is done in a structured manner and is as complete as possible,
3. semi-guided interviews in which the specialists concerned give binary appreciation of the assets that seem to them to have greater vulnerability to submersion,
4. validation of the coherence of the responses of the experts and calculation of elements with risk vulnerability weightings,
5. synthesis of the responses to provide the vulnerability coefficients.

3.1.3. Structured hierarchy of the system

A hierarchical breakdown (also called a vulnerability index) was plotted with local stakeholders to provide an overall description of the situation. This was a specific hierarchy of the area and based on typology combining the three main categories of assets and their vulnerability factors (Figure 3).

There are six types of equipment and environmental assets. If need be, they can be given sensitivity factors, as was proposed by Léone (2007) and Propeck-Zimmerman et al. (2009): these are intrinsic features of the elements in question and affect their vulnerability. Indeed, as regards equipment assets, the characteristics of the buildings modulate the vulnerability of housing, and the sensitivity of environmental assets can take into account the state of fields and the types of crops. Finally, human assets are divided into six categories with sensitivity factors. The latter make it possible to use simple residential density, often considered as the most obvious vulnerability factor. However, it also traces the concentration of resources allowing a rapid, effective reaction to emergency situations, although according to the police and gendarmerie and the fire brigade, all the communes in Greater Lyon can be reached in less than 10 minutes (Rufat 2007). These features mean that analysis of the resident population should be refined by sensitivity factors, as for the other types of population. Indeed, the consequences of catastrophes resulting from the same risk differ from one category of persons to another. According to Cutter et al. (2003), Holand et al. (2011), Dauphiné and Provitolo (2013), Armenakis and Nirupama (2013b) or Koks et al. (2015), groups of persons less than 10 years old and over 75 years old are more fragile and evacuation is more difficult if this should be necessary. The same applies to people with reduced mobility. Persons in makeshift shelters are also more fragile and more exposed to all kinds of risk (Rufat 2007). Furthermore, education level was also used as an indicator of the ability to find solutions in case of catastrophe, with capacity being proportional to this level (Cutter et al. 2003; Kreimer et al. 2003; Borden et al. 2007), leading us to taking into account the population of persons over 15 years old with no qualifications.

For human assets, this hierarchical structure was constructed using the INSEE census at the scale of IRIS\(^1\) (the last census available (2011) has been used here). Information on environmental and equipment assets were drawn from the GIS database for Greater Lyon. However, sensitivity factors for equipment and environmental assets have not been taken into account for the moment. Application of the study to these sensitivity factors is a future prospect in this work.

Asset prioritization was performed in collaboration with local stakeholders. However, it is in no way definitive and features such as assets and sensitivity factors can be enriched according to operational use and the gaining of knowledge on the question. This continuous improvement feature is a strong point of the method and thus favours use by local stakeholders.

3.1.4. Use of the judgement of specialists for calculating priorities

Evaluation of the vulnerability of assets is based on the judgement of 38 local experts, derived using a matricial calculation. Local government employees (local government engineers and technicians) formed 50% of the experts, 30% were consultants (Veolia, Lyonnaise des Eaux, Egis, etc.) and 20% were academics (mainly at University Jean Moulin Lyon 3 and University Lumières Lyon 2), chosen...
for their professional involvement in land use planning, urban planning, management and risk prevention. They also validated the vulnerability index previously established (Figure 3).

This quantification is based on two by two asset comparison using a specific scale based on Saaty’s criteria (1980 – Table 1). The evaluation grid has the advantage of measuring both subjective and formally quantitative judgements in order to gauge the degree of vulnerability of one of the assets in the hierarchy in relation to another. For example, as shown in Table 2, for human assets experts have to compare the vulnerability of the residential population with the working population, the transit population (Are people more vulnerable during a disaster at home, at the workplace or in a car?) and so on, using the binary comparison scale shown in Table 1. On completion of this procedure, each asset is compared to all the others of the same order that have the same rank in the hierarchic index (Figure 3).

The comparison matrices with input from specialists’ judgements are then used to calculate the vulnerability of each asset. A coherence ratio is also calculated to validate the coherence of the vulnerability index.
replies and the transivity of judgements and inconsistent replies are deleted. For example, if an expert indicates a greater vulnerability of target A relative to target B, and a greater vulnerability of target B versus C, in all consistency he will indicate greater vulnerability of target A compared to C (transitivity of judgments).

The replies are then aggregated by geometrical average to form a single comparison matrix (Tixier et al. 2006). Finally, judgement matrix vectors were calculated to give functions that determined vulnerability weightings.

3.1.5. Reflection on the framework of analysis

AHP is used here to establish weightings of vulnerability between the assets of Greater Lyon (Figure 3). However, once set using functions and for operational use, these priorities must be shown in map form. A GIS is therefore used to spatialize, process, store and analyse the heterogeneous data concerning the assets. The GIS is used for both quantitative and qualitative mapping of assets according to the various functions and also allows analytical questioning. However, the graphic representation of assets is handled in different spatial ways: surface area, linear or points. The question of the sector of exploration of assets then arises, as these must be rationalized with regard to their combination. Previous studies were based on the boundaries of towns or IRIS units. But the range of sizes of these study sectors means that quantitative comparison of zones cannot be made, or only in a relative manner with the rationalization of the assets in each zone using the area concerned. In addition to a great variety of surface areas, the different shapes of towns or IRIS made it impossible to compare one zone with another and affected the interpretation of the results. We therefore chose standard sizes and forms of sectors to be able to work on raw data (and not relative data according to area) and facilitate comparison of zones and the understanding of results while avoiding commune (local authority) boundaries and INSEE zones. A grid consisting of sectors of identical size and shape was thus used. Two types of squaring are in common use: a square mesh or a hexagonal mesh (often referred to as a honeycomb (Kienberger et al. 2009). We chose a square mesh for reasons of simplicity. This squaring of the study zone seemed more appropriate and operational than the spatial scale used in previous studies of Greater Lyon that were based on unsuitable exploration sectors affected by constraints.

Surface area, linear or point assets were converted into a grid by a GIS and quantified according to areas, lengths or the sum of components in the grid. Grid size must be adapted to the degree of

| Degree of vulnerability | Definition |
|-------------------------|------------|
| 1                       | Equal vulnerability of two elements |
| 3                       | Low vulnerability of an element in comparison to the other one |
| 5                       | High vulnerability of an element in comparison to the other one |
| 7                       | Certified vulnerability of an element in comparison to the other one |
| 9                       | Absolute vulnerability of an element in comparison to the other one |
| 2, 4, 6, 8              | Intermediate values between two appreciations |
| 1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9 | Reciprocal values of the previous appreciation |

Table 1. Scale of binary comparison used to assess the vulnerability of assets (adapted from Saaty 1980).

Table 2. Example of a matrix used by experts to determine the vulnerability of human elements at risk, using the scale of binary comparison (given in Table 1).
accuracy of the data and also to the space studied and its own problematics. Squares 100×100 m were chosen and an area of 10,000 m² provides a good compromise between the size of the area examined (515 km²) and the number of grid squares created in this way (89,804).

Coarser squaring had been used (for example, in Renard & Chapon 2010) with 500 m × 500 squares. Although the cartographic rendering made it possible to bring out certain vulnerable zones, local stakeholders could not use the findings because the end-result was imprecise. Using a finer grid improves the quantitative and qualitative structuring of assets and thus limits the uniformization of information as the assets are not necessarily distributed evenly in the grid.

The assets are weighted using pre-established priority functions according to their nature, and must also be weighted according to their area in the field in each of the grid squares. A quantification factor is defined as being a dimensionless variable on a scale of 0 to 1. A 0 means that there are no assets in the grid square and 1 means that the quantity of this asset is the largest in comparison with the other squares. The quantification factors therefore lead to standardized quantification for each asset (Figure 4) and standardized representations of the vulnerability of assets in Greater Lyon, whatever their nature and the level of hierarchical breakdown considered.

3.2. Analysis of spatial autocorrelation and clusters for identifying priority zones

The identification of geographic models is fundamental in understanding the behaviour of spatial phenomena (Griffith 1987). Model analysis in this study allows the identification of clustering or dispersion trends in the spatial distribution –random or not – of vulnerability. Statistically significant spatial clusters (hot and cold spots) or aberrant spatial points are then identified. The aim is the identification of key sectors with high vulnerability, going beyond the framework of simple cartography. Indeed, although it is possible to perceive an overall model of entities and their values by mapping them, statistical calculation quantifies the model. Comparison of models for different distributions or time periods is made easier.

3.2.1. Exploration at the overall level: Moran’s index and the General G statistic

Spatial autocorrelation in the study was determined using Moran’s index (Getis 1991; Anselin 1999), and the degree of clustering of high or low values was measured using the Getis–Ord General G tool (Getis & Ord 1992). Moran’s index of spatial autocorrelation measures the latter according to entity positions and values. Using an ensemble of entities and the associated attribute, it provides evaluation of whether the model is clustered, dispersed or random, using a value of -1 to 1.

Moran’s I statistic is calculated as

\[
I = \frac{n}{S_0} \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} (x_i - \bar{X})(x_j - \bar{X}) \sum_{i=1}^{n} \sum_{j=1}^{n} z_i^2,
\]

where \( w_{ij} \) is the spatial weight between features \( i \) and \( j \), \( z_i \) is the deviation of an attribute for feature \( i \) from its mean \( (x_i - \bar{X}) \), \( \bar{X} \) is X mean, \( n \) is the total number of features, \( S_0 \) is the sum of all the spatial weights:

\[
S_0 = \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}.
\]

The \( Z_I \)-score for the statistic is computed as

\[
Z_I = \frac{I - E[I]}{\sqrt{V[I]}}
\]

where

\[
E[I] = -1/(n - 1),
\]

\[
V[I] = E[I^2] - E[I]^2.
\]
Assets can be mapped as:

\[ G = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j} x_i x_j}{\sum_{i=1}^{n} \sum_{j=1}^{n} x_i x_j}, \forall j \neq i, \]  

(2)

where \( x_i \) and \( x_j \) are the attribute values for features \( i \) and \( j \), and \( w_{i,j} \) is the spatial weight between feature \( i \) and \( j \). The \( z_G \)-score for the statistic is calculated as

\[ Z_G = \frac{G - E[G]}{\sqrt{V[G]}}, \]
where

\[
E [G] = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}}{n(n-1)}, \quad \forall j \neq i
\]

\[
V [G] = E[G^2] - E[G]^2.
\]

These statistics are inferential, meaning that the basic hypothesis stipulates that the values have random distribution *a priori* (i.e. null hypothesis, also known as complete spatial randomness, CSR). A *p*-value is thus calculated and represents the probability that the null hypothesis is correct, that is to say that the distribution observed is just one of many random possibilities of dispersion, and also gives a Z-score. Interpretation of the results of these two spatial statistics tools is therefore performed according to the *p*-values and *z*-scores related to the rejection or not of the null hypothesis (Anselin 1999).

### 3.2.2. Exploration at the local level: local Moran’s I and the Getis–Ord Gi* tools

The local declination of Moran’s index, referred to as *Anselin Local Moran’s I* or *Local Indicators of Spatial Association* – LISA (Anselin 1995) is used to identify both spatial clusters of entities with values of the same magnitude and aberrant spatial points. Thus the results for very low *p*-values (<0.05) can distinguish between a statistically significant high-value cluster (HH) and low values (LL) and an aberrant point where a low value is surrounded mainly by high values (LH). HL aberrant points are the most important for vulnerability management, along with HH clusters, as these zones are more difficult to distinguish. Indeed, attention is drawn more readily to clusters with HH high values.

The local declination of General G, the Getis–Ord Gi* statistic (Getis & Ord 1992; Ord & Getis 1995; Getis & Ord 1996), can be used to identify significantly significant spatial clusters of high values and low values, but as long as the *p*-values are very low. This statistic is also useful in questions of development as an entity with a high value can be interesting but possibly not a statistically significant hot spot. Thus, the higher its value for statistically significant *z*-scores, the more intense the cluster of high values (hot spot). Inversely, the lower a statistically significant negative *z*-score, the more intense the cluster of low values (cold spot). Here, we therefore focus above all on the hot spots with the greatest vulnerability.

### 4. Results: the vulnerable zones are not only in the centre

#### 4.1. Weighting functions and cartographic processing

The results make it possible to award vulnerability of the assets of Greater Lyon by establishing weighting functions. They group all the assets with the same level of hierarchical breakdown by awarding a weighting that differs depending on vulnerability. These functions show the preponderant share of human assets (73.5%). Léone (2007) even refers to these as supreme assets to be preserved. Equipment vulnerability represents 20% of the vulnerability function, while environmental vulnerability represents 0.65%:

\[
\text{Vulnerability}_{\text{total}} = 0.735 \text{ Vulnerability}_{\text{human}} + 0.064 \text{ Vulnerability}_{\text{environmental}} + 0.201 \text{ Vulnerability}_{\text{equipment}}. 
\] (3)

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Likewise, vulnerability is obtained for each level of the index. For example, the vulnerability of the networks is given as

\[ \text{Vulnerability}_{\text{network}} = 0.22 \times \text{Vulnerability}_{\text{water system}} + 0.249 \times \text{Vulnerability}_{\text{sewer system}} + 0.185 \times \text{Vulnerability}_{\text{electricity}} + 0.085 \times \text{Vulnerability}_{\text{chemicals}} + 0.104 \times \text{Vulnerability}_{\text{hydrocarbons}} + 0.157 \times \text{Vulnerability}_{\text{telecommunications}}. \] (4)

All the responses given by the experts lead to a global consensus for every level of the vulnerability index. This general agreement could be explained by the fact they have common experience and sometimes mutual education, often working together on the same subject. Standard deviations were calculated for each vulnerability element and are fairly low, except for urban furniture where a small disagreement appeared. Indeed, information furniture is the most vulnerable asset in the face of floods for about 70% of the experts, whereas it is bus shelters for the others (see Figure 3).

The final aim of the study is the mapping of the vulnerability of elements in Greater Lyon. Human, environmental and equipment vulnerability of the assets are represented spatially, qualitatively and quantitatively in Figure 5.

The decreasing gradient of human vulnerability from the centre to the outskirts is correlated with equipment vulnerability (Figure 5). Indeed, equipment elements such as buildings and transport infrastructure are grouped in the urban centre of Greater Lyon and concentrated in areas with high population density. This equipment distribution accounts for the distribution of environmental vulnerability. Indeed, the areas that are poor in equipment elements are rich in environmental assets. Environmental vulnerability is thus found mainly in the peripheral area.

Another distribution of vulnerability could have been obtained if the judgements of the experts had been different. Indeed, for example, if they had weighted the environmental elements as the most vulnerable (before human and equipment elements), the map would have shown an increasing vulnerability gradient from the centre to the periphery. Thus, the final vulnerability map depends directly on the distribution in the area of the different kinds of elements at risk, but also to a considerable extent on the weighting given by the experts.

It is very useful for decision makers to have an accurate view of vulnerability throughout the Lyon urban area, and not just in a few sectors, as practically the whole of Greater Lyon is potentially at risk from precipitation hazards.

Although this approach describes multiple operational interests, limits must be set to define its real indicative value in the evaluation of vulnerability and the handling of risks.

4.2. Some clusters of high vulnerability located in the outskirts

The spatial autocorrelation results show that the \( p\)-value is statistically significant and that the Z-score and Moran’s index are positive (Table 3). The null hypothesis can therefore be rejected and the spatial distribution of high values and/or low values for vulnerability display stronger spatial clustering than if the underlying spatial processes were random. It is noted that the output of the model varies slightly according to the type of conceptualization of the spatial relations used (Table 3 – Anselin et al. 2010; Oliveau 2010). Analysis of spatial clusters confirms these results. Indeed, the \( p\)-value is statistically significant and the Z-score is positive: the null hypothesis is therefore rejected. Thus, the spatial distribution of the high vulnerability values in the data set displays stronger spatial clustering than if the underlying spatial processes were random. These first overall results make it possible to move on to the next step to define key zones for vulnerability management.

Application of local Moran’s I and the Getis–Ord Gi* spatial statistics provides information about the key sectors of the urban area (Figure 6). The main zones of high vulnerability (HH) are located in the centre of the agglomeration, according to the previous results (§ 4.1). However, other zones of
High vulnerability can be identified outside the urban core, located in the nearby outskirts in the north–east, east and south–east (Figure 6(a)), which did not appear clearly on the global map (Figure 5). Moreover, the Getis–Ord Gi* spatial statistics identifies certain high vulnerability hot spots in a very precise manner, mainly in the centre of Lyon. In addition, LISA indicates some clusters of high vulnerability around Lyon in the north and east, far from the centre. These high vulnerability zones and clusters of must be taken into account carefully for local risk management and should not to be forgotten when focus is on the core of Lyon. In a general manner, these results tend

Figure 5. Greater Lyon vulnerabilities. Top: overall vulnerability – bottom left: human vulnerability – bottom centre: environmental vulnerability – bottom right: equipment vulnerability.
to agree with those obtained in the previous step and displayed in Figure 5. This is due to the residential and economic density of the centre of Greater Lyon.

4.3. The limits of the method proposed and the potential for upgrading

This methodology proposed for the territorial analysis of vulnerability—applied to the Lyon urban area in this case—addresses gaps in previous studies on the same area, in particular by using multicriterion hierarchic analysis of the priority of assets for the first time. However, this type of method using a spatial systemic, qualitative and quantitative approach has limits that must be taken into account for subsequent improvement of the study.

Certain limits of the multicriterion decision aid method chosen must be taken into account, even though it is used in many varied fields (Al-Harbi 2001; Al Khalil 2002; Nassar et al. 2003; Hill et al. 2005). AHP has sometimes been called into question, in particular by Saaty himself (Saaty & Hu 1998) and by other authors (Dyer 1990; Harker & Vargas 1990 for example). It is noted in particular that weightings are ascribed independently of the scale of variation of indicators. Thus two indicators may have the same weighting whereas one of them has greater variation amplitude. In addition, the introduction of new indicators changes the priority of the other indicators and rank inversion may occur. However, Harker and Vargas (1990) and Pérez (1995) examined these criticisms and used theoretical work and concrete examples to show that they were not valid.

The validity and legitimacy of the ranking created from matrices then drew criticism and the two by two comparisons of elements of the same level, greater than seven, can sometimes be complicated for specialists (Donegan et al. 1992; Dodd et al. 1995). The problem can perhaps be solved but making associations of assets with the same hierarchical level in spite of the resulting loss of accuracy and significance (Dodd et al. 1995). Finally, the coherence of the judgement of the specialists was evaluated using an incoherence ratio. However, the latter was called into question because of its rudimentary aspect and lack of rigidity for low order matrices which also tended to be located at high levels of the hierarchical breakdown (giving them greater influence and range than the high order matrices close to the base—Donegan et al. 1992; Dodd et al. 1995)

| Conceptualization of spatial relations | Moran’s index | Z-score | p-value   |
|--------------------------------------|---------------|---------|-----------|
| Inverse distance squared             | 0.95          | 323.4   | <0.001    |
| Fixed distance band (1 km)           | 0.64          | 1960.5  | <0.001    |
| Polygon contiguity                   | 0.95          | 323.4   | <0.001    |

Figure 6. Zones and clusters of vulnerability shown by LISA (a) and high vulnerability hot spots (b) in Greater Lyon.
The representativeness of the panel of specialists is another limiting factor for the method. We observe that the specialists gave slightly different responses according to their professions and specializations, especially for the matrices close to the base of the hierarchical tree. Their judgement, even if they are specialists and even because of this, remains partially arbitrary. However, our panel of specialists had an overall consensus of opinion and did not call into question either the bases of the method or the results obtained.

6. Conclusion

Risk management has long been based solely on the knowledge and mastery of hazards. Shared by numerous scientific disciplines, by stakeholders and local elected officials, the notion of vulnerability appeared more recently and now forms a field of research in its own right. Studies aimed at improving knowledge of vulnerability have shown both their usefulness and also their limits. Methodology has therefore been proposed here that is aimed at the qualification and spatial quantification of vulnerability. It can be adapted to all hazards and all sites and takes into account all the assets in the study and uses decision aid methods and GIS geomatic processing. Maps of vulnerability are therefore provided. Finally, analysis of autocorrelation and clusters is proposed to refine analysis and go beyond the simple cartography of variables. The recomposition of vulnerability has highlighted key sectors in the urban area and islands of high vulnerability that are initially less distinct, providing local stakeholders with a set of key zones for the improvement of risk management policies.

Note

1. *Ilots Regroupés pour l'Information Statistique*: the smallest demographic census unit in France, focusing on between 1,800 and 5,000 persons.

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