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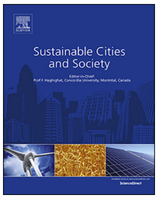

Mapping urban resilience to disasters – A review

Jean-Marie Cariolet*, Marc Vuillet, Youssef Diab

Lab'Urba EA3482, Ecole des Ingénieurs de la Ville de Paris, EIVP, Paris, France

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ABSTRACT

Maps and Geographic Information Systems (GIS) are widely used to better understand and manage risks in modern cities. While methods for mapping hazard, vulnerability and risk are well established, mapping resilience in urban areas poses a challenge as there are no agreed-on methodological approaches for doing so. This paper surveys proposed methodologies and approaches for mapping urban resilience to disasters. Our review shows that (1) adaptive resilience is mapped after a disaster mainly through the measure of recovery and inherent resilience is mapped using top-down approaches. Regarding inherent resilience (2), very few methods have been applied at city scale; (3) the limit between resilience and vulnerability mapping is still narrow and may cause confusion for decision makers; (4) the choice of variables and indicators to measure and map resilience is often a function of data availability and reliability; (5) indicators developed in one specific context should not be applied systematically to other contexts as resilience is a context-dependent concept; (6) most resilience maps are based on an analytical approach and do not reflect the systemic property of resilience.

1. Introduction

1.1. Maps and GIS for disaster management

Geography plays an important role in many decision-making issues, especially for cities. Maps make it possible to identify and understand complex spatial problems (Klimešová & Brožová, 2012). In other words, maps help decision-makers to detect problems and find solutions and thus help create new knowledge (Crampton, 2014). For a long time now, maps have been used to understand the geographic context of disasters in a wide range of military, engineering or urban planning domains (Tomaszewski, 2015).

Since the 1990s, Geographic Information Systems (GIS) have been a powerful tool for presenting and analyzing layers of information in a spatial way. One of their objectives is to provide easily understandable scientific information for decision makers. GIS-based decision-support tools improve communication between researchers and decision-makers and provide a platform for interdisciplinary study by reducing the gap between research and decision-making (Ren et al., 2013). GIS has become an important decision-making support and information management tool for many aspects of disaster management (Tomaszewski, 2015). They have been widely used to produce hazard, vulnerability and risk maps to understand and manage risks in cities more effectively (Cova et al., 1999). However, for several years, a new concept has been increasingly mentioned to manage risks in cities and integrated into public policy - the concept of urban resilience. It is therefore important to explore the most appropriate ways of mapping this concept and understanding the added-value of making and using resilience maps.

1.2. Urban resilience, a new paradigm

Following recent disasters such as hurricanes Katrina (2005) and Sandy (2012) in the USA, the concept of resilience has emerged globally as a new risk management and disaster mitigation paradigm (Landau & Diab, 2016). The term resilience has been defined in many ways as already discussed elsewhere (Alexander, 2013; Cutter et al., 2008; Meerow, Newell, & Stults, 2016). Regarding urban resilience more specifically, Meerow et al. (2016) note that the concept is also characterized by conceptual tensions and they propose a broad definition based on a review of literature:

"Urban resilience refers to the ability of an urban system-and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales-to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity." (Meerow et al., 2016; page 39)

This definition highlights the fact that resilience has a systemic property (Reghezza, 2016) and implies greater consideration of the time variable.

Besides urban resilience, North American researchers often refer to

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* Corresponding author.
E-mail address: jean-marie.cariolet@eivp-paris.fr (J.-M. Cariolet).

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community resilience to study resilience at the community level and this approach incorporates an important social component. As community is considered a system of interconnected systems (Cutter, 2016) we may consider community resilience in urban areas as similar to urban resilience (and this approach will be taken in this article).

1.3. *Objectives of the review*

This paper aims to understand how urban resilience to disasters is mapped by researchers. The usefulness and reliability of the identified cartographic output will also be examined. Although Renschler et al. (2010) assumed that GIS play a major role in assessing system resilience, there is still a need to understand exactly how. We have analysed scientific articles and reports whose results included resilience maps to disasters of urban territories, urban infrastructures or urban communities.

2. Methodology

This study follows qualitative systematic review principles. Studies were searched using the Scopus and Web of Science databases using the following combination of keywords (“map” OR “G.I.S” OR “score” OR “assess” OR “index”) AND “urban” AND “resilience” AND “disaster”. In addition to the articles identified through database searching, additional articles identified prior to this work were included. As we focus our review on urban resilience, this paper aim to discuss case studies at the city scale. However, because examples at the city scale are so scarce, studies performed at regional or national scale have been added to this review when they provide relevant information for our analysis.

After duplicated studies were removed, remaining articles were screened based on title and abstracts. At this step, articles were selected based on the following inclusion and exclusion criteria:

- Inclusion criteria: (1) article published in English; (2) article focusing on urban resilience
- Exclusion criteria: (1) article focusing on hazard, vulnerability, impacts, or risk assessment (2) article focusing on solutions for enhancing resilience; (3) reviews (reviews are eliminated if they do not have the same aim as our review)

The remaining articles were screened based on full-texts and figures. Articles with at least one map linked with the concept of resilience were selected (Fig. 1).

The 48 papers were read in full and then categorized and analyzed by the first author. This was done following a methodology developed by all three authors, which relies on a descriptive analysis of the methods developed to produce resilience maps in the 48 papers. For each paper, the following items were analyzed: (1) what type of resilience is mapped? (eg. resilience in the sense of recovery after a disaster, resilience as opposite to vulnerability, resilience as an inherent capacity) (2) Is the method intended to map the resilience of a territory, a community or a specific urban object? (3) What is the scale and the spatial unit used? (4) Is the method based on a top-down or a bottom-up approach? (4) Is the method based on a systemic approach?

3. Results

By nature, resilience can be observed and characterized only after a disaster, making it difficult to measure – and thus to map – before a disaster occurs. However, decision-makers often need to assess resilience before disasters take place in order to improve urban resilience while “there is still time”. This difficulty has led researchers to propose two ways of measuring - and thus map - resilience. Cutter (2016), Rose (2004) and Tierney (2007) distinguish between adaptive resilience and inherent resilience. Adaptive resilience relates to the post-event process and outcome and can be measured only after a disaster. Inherent resilience is often termed resilience capacity, i.e., the inherent attributes that enable a community or a territory to respond to and recover from shocks (Foster et al., 2012). In theory, Inherent resilience can be measured before an event and may serve as a baseline for improving urban resilience. In this paper, we consider these two types of resilience in terms of measurement before an event (inherent resilience) or after an event (adaptive resilience) (Fig. 2). This is a simplified vision of the concept of resilience, but it enables to distinguish clearly two kinds of mapping with respective goals.

Regarding adaptive resilience, the review shows that maps aim to plot the post-disaster spatial distribution of resilience mainly through the concept of recovery. Regarding inherent resilience, most of the maps found in research literature aim to assess pre-disaster resilience capacity or inherent resilience. In other words, these maps depict resilience not as a process but as a capacity that urban systems have to be resilient to shocks. This category of maps can be useful for showing decision-makers how to locate the weak points in a city and for enhancing pre-disaster urban resilience. The methods developed to produce these kinds of maps are numerous and indicative of the vagueness of the concept of resilience.

3.1. *Mapping adaptive resilience*

Most adaptive resilience mapping is done after disasters by network operators, cities and sometimes by researchers. After Hurricane Sandy in New York in 2012, the recovery time for telecommunication services (The City of New York, 2013; page 166) and the subway network (Fig. 3) has been depicted. Maps were updated as service was restored and posted on social media in order to inform populations. Those maps express the post-hurricane adaptive resilience of these two urban subsystems.

Recently, maps have also been produced to demonstrate the spatial and temporal distribution of power outages during - and the recovery of the power grid after – Hurricane Irma in Florida in September 2017 (Fig. 4). These kinds of maps show that power grids in some counties were less resilient than others.

In scientific literature, Miles and Chang (2011) managed to map recovery time after the 1994 Northridge earthquake in the county of Los Angeles. For example, the authors mapped the number of weeks needed to rebuild damaged residences or the percentage of households still left five years after the disaster.

Lam, Arenas, Pace, LeSage, and Campanella (2012) have mapped business return in New-Orleans after Hurricane Katrina (Fig. 5). The authors showed that the two most important predictors were the flood depth and business size.

Contreras, Forino, and Blaschke (2018) have mapped the evolution of recovery of L’Aquila (Italy) following the earthquake of 2009, based on the calculation of a recovery index for the years 2010, 2012, 2014 and 2016. The recovery index is based on building condition and building use evaluation. According to the authors, the recovery index is useful for identifying spatial pattern – such as hot spots - of the recovery process.

This type of experience/feedback-based mapping focus mainly on the post-disaster recovery process of specific elements or sub-systems of what constitutes urban resilience, but do not depict the possible changes of trajectories for a city. However, what is actually mapped at a given moment might not depict a bounce-back outcome, but might be a temporary unstable state.

3.2. *Mapping inherent resilience*

3.2.1. *Bottom-up and top-down approach*

Cutter (2016) distinguishes two kinds of methodological approaches to assess the resilience of a community: bottom up and top down. Bottom-up approaches are often qualitative and measure the resilience of institutions or governance structures. According to Cutter (2016),

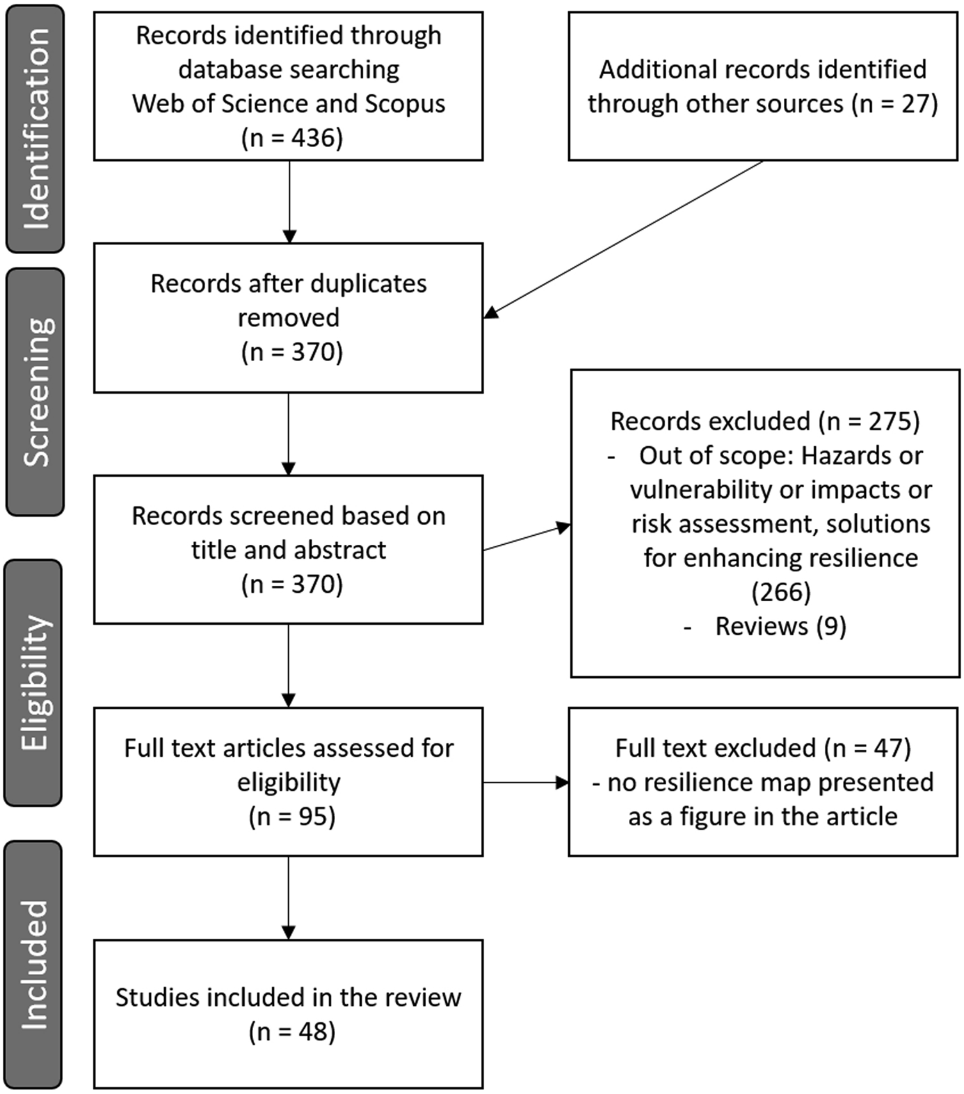

Fig. 1. Systematic review summary.

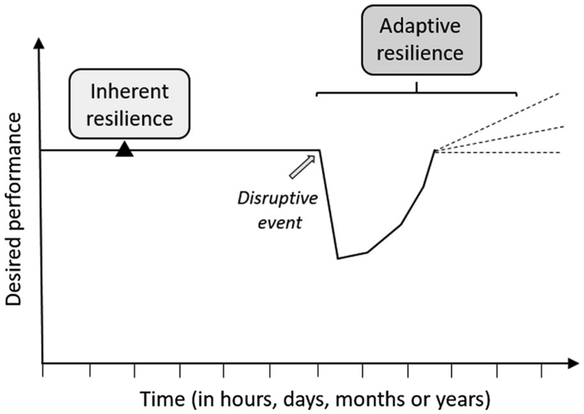

Fig. 2. Difference between adaptive and inherent resilience. Adaptive resilience can be observed and measured after a disaster, while inherent resilience is the capacity of the system to be resilient in the face of a disruptive event.

“the ability to compare across places” using bottom-up approaches “is difficult because of the variability in data, and the different contexts and meanings of resilience” (page 745). For these reasons, and also because most of the data used in these methods are not available spatially or even mappable, this kind of approach does not enable the production of maps. Many cities around the world are currently using bottom-up approaches, such as the city resilience index developed by Arup and used in the 100 Resilient Cities network (Spaans & Waterhout, 2017), or the urban resilience index developed by the International Environment and Disaster Management Laboratory in Kyoto (Kabir, Sato, & Yousuf, 2018).

Top-down approaches use available data and quantitative methods for calculating resilience indicators for specific units of analysis (district, region, state, etc.) depending on the scale of a case study and on data. Within the resilience community, they are often expressed by a score from 0 to 1. According to Cutter (2016), this type of approach can be used to examine spatial variability. Most inherent resilience maps are produced using a top-down approach. Indeed, map producers usually use global indicators as it is not generally possible to factor in the real complexity of urban resilience.

Inherent urban resilience is currently mapped in many ways by using available data. Firstly, we will see that one of the first solutions researchers found for mapping inherent resilience was to map the opposite of vulnerability. We will then focus on the capacity approach which helped to map inherent resilience more effectively.

3.2.2. *Using the opposite of vulnerability to map resilience*

The concept of resilience is sometimes considered the opposite of vulnerability (Bates, Angeon, & Ainouche, 2014; Folke et al., 2002;

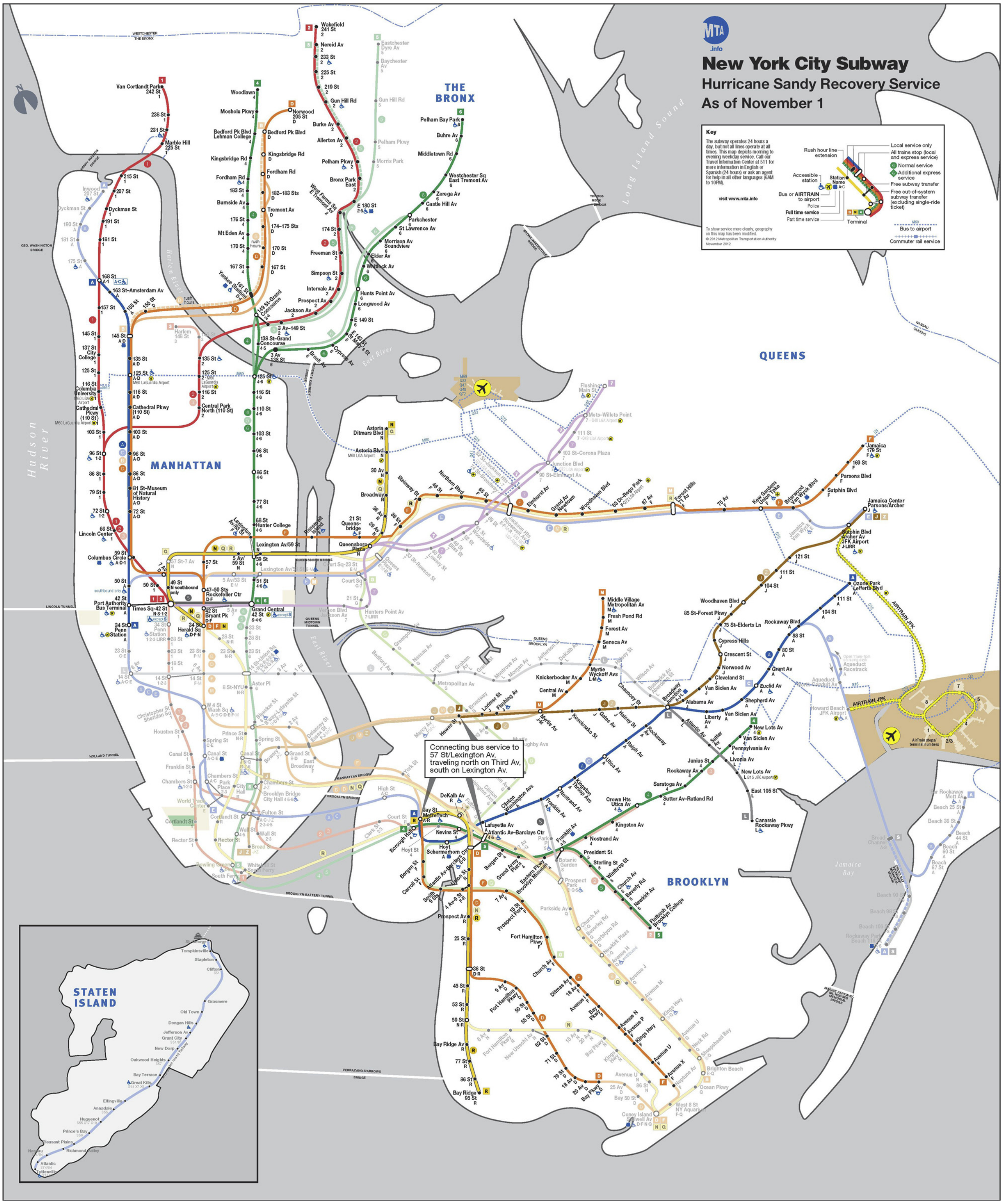

Fig. 3. Recovery of the New York City subway after hurricane Sandy, on the 1 st of November 2012 (source: MTA).

Gallopin, 2006), as vulnerable territories tend to be less resilient (Bergstrand, Mayer, Brumback, & Zhang, 2015). This helped give resilience an operational and understandable definition, and the positive connotation of resilience - unlike vulnerability – facilitated its applicability (Reghezza-Zitt, Rufat, Djament-Tran, & et Serge Lhomme, 2012). According to this principle, certain mapping methods consider that low vulnerability is equal to high resilience and thus use traditional vulnerability indicators to devise resilience indicators (Highfield, Peacock, & Van Zandt, 2014; Jabareen, 2013; Van Zandt et al., 2012). Other approaches such as the *Resilience Atlas*[1] do not even consider the “flip-side” of vulnerability, but use exposure and vulnerability analysis directly to produce what they call resilience maps. According to Reghezza-Zitt et al. (2012), it is not always possible to oppose resilience

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[1] https://www.resilienceatlas.org

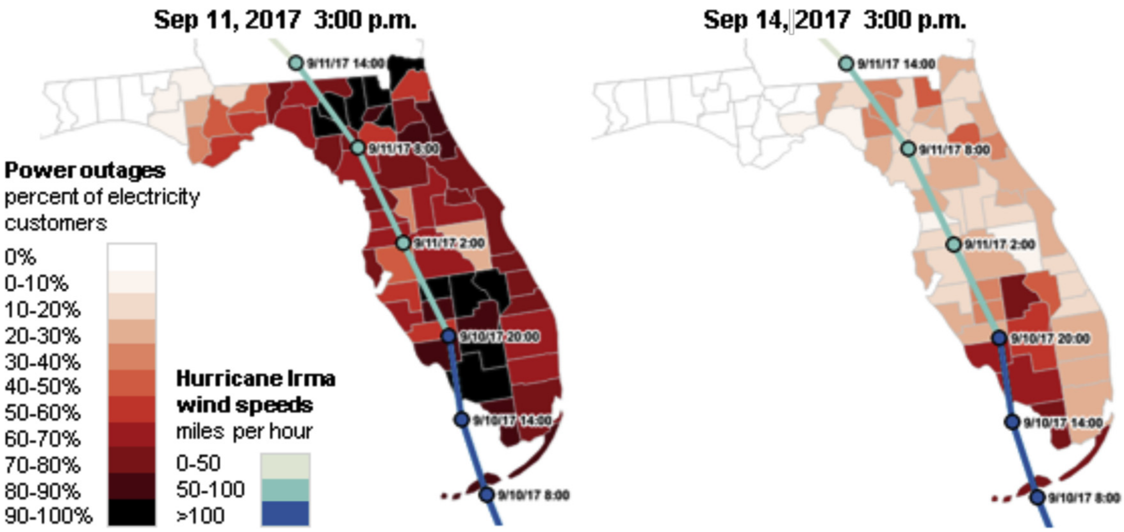


Fig. 4. Florida power outages by county after Hurricane Irma between the 11th and 14th of September 2017. The hurricane crossed Florida during the 10th and 11th of September 2017. Source: U.S. Energy Information Administration based on data from the Florida Division of Emergency Management and NOAA National Hurricane Center.

and vulnerability as a vulnerable system may be resilient and vice-versa. History shows that cities are vulnerable to natural hazards but often resilient, as very few cities have actually disappeared over the centuries (Vale & Campanella, 2005). Reghezza-Zitt et al. (2012) go further by arguing that "there can only be resilience if an impact and a disruption occur, which analytically, implies vulnerability". Therefore, resilience cannot be measured by using the opposite of vulnerability. Another way of quantifying resilience, namely the capacity approach, has helped operationalizing the concept.

3.2.3. The capacity approach

The variables used to build resilience indicators are often based on resilience principles (or properties), which are considered the general attributes that a resilience system should possess (Sharifi & Yamagata, 2016) and they have helped researchers to develop resilience indicators in different domains such as ecology, psychology, urban sciences, etc. These principles are numerous - robustness, stability, flexibility, redundancy, resourcefulness, diversity, independence, self-organization, agility, omnivory, homeostasis, high flux, buffering, flatness, etc. – and

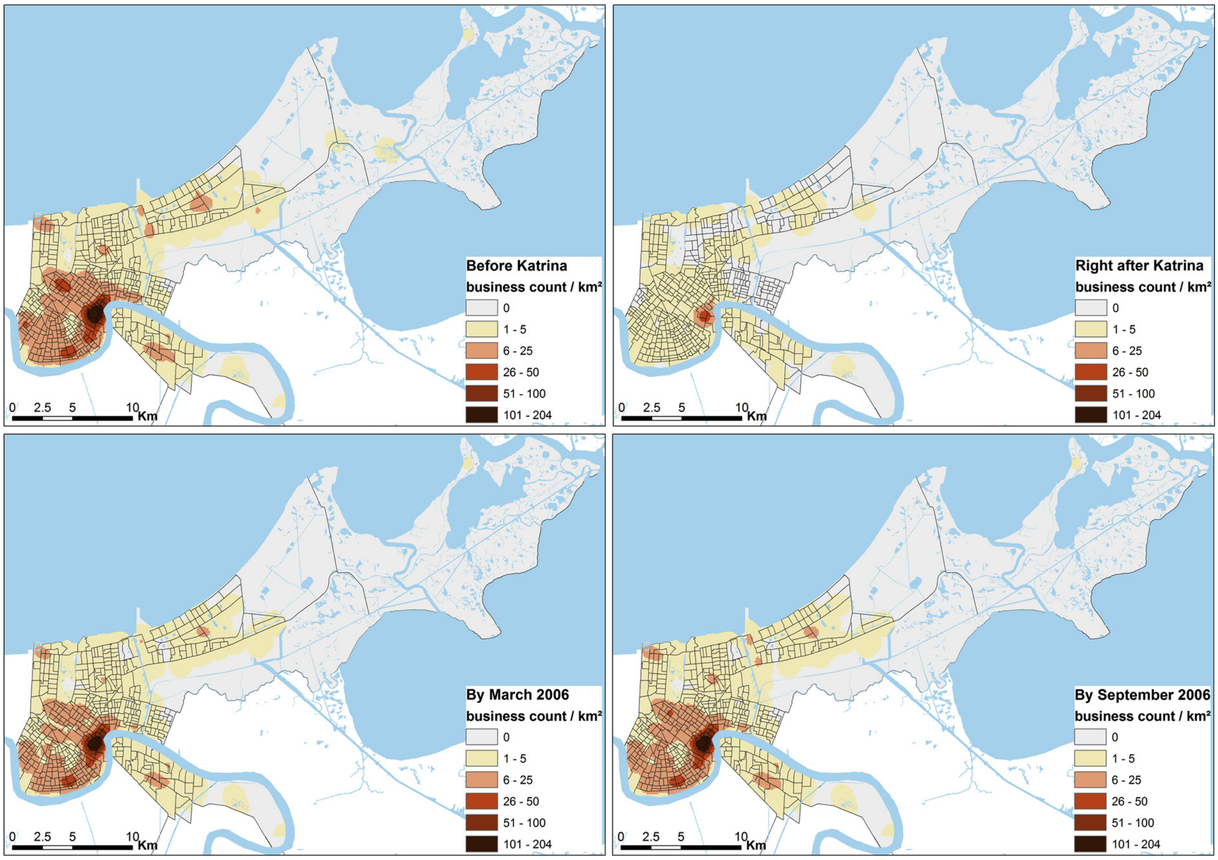


Fig. 5. Density maps of opened businesses in New Orleans before, during and after hurricane Katrina (Lam et al., 2012).

their definition has already been discussed elsewhere (Biggs, Schlüter, & Schoon, 2015; Touili & Vanderlinden, 2017; Sharifi & Yamagata, 2016; Wardekker, 2018). What is interesting here is that these principles can be applied to any system, making it a powerful approach.

The seminal paper written by Bruneau et al. (2003) proposed a framework for assessing community resilience by evaluating four principles that define the capacity of communities to be resilient: robustness, redundancy, resourcefulness and rapidity. According to the authors, these principles need to be quantified around four technical, organizational, social and economic dimensions. This work helped operationalizing the concept of resilience through the notion of capacity and its associated principles.

In 2007, Foster proposed a Resilience Capacity Index (RCI) which was calculated at regional level and then mapped at national level. The RCI is based on the calculation of 12 indicators, including economic, demographic and social connectivity factors. This method has been applied in the USA (Foster, 2007) and in Slovakia (Hudec, Reggiani, & Siserova, 2018). The capacity approach has inspired many other researchers (Cutter, 2016) but only a few methods propose maps as outputs. Among these, we have especially identified holistic approaches that measure the resilience of a community or territory to any kind of hazard along different dimensions (i.e., technical, social, economic, etc.).

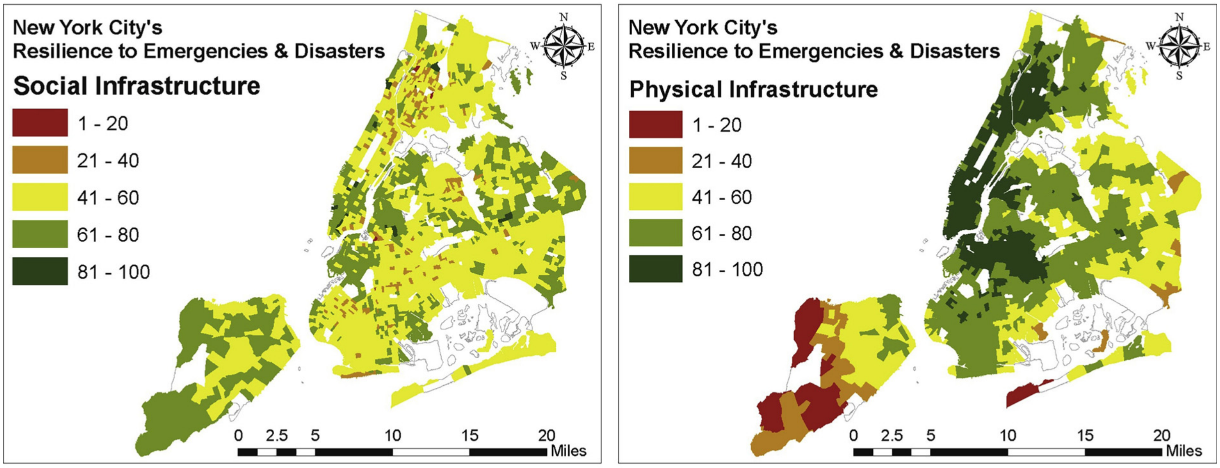
3.2.3.1. Holistic resilience indicators. Studies using a holistic approach to map resilience of a territory are listed in Table 1. Many identified holistic approaches use spatial units which are larger than cities. Although these approaches do not map urban resilience specifically – because of their broad granularity – they are worthwhile analyzing for the purposes of this review as they are based on variables that could be used on an urban scale.

For instance, Cutter, Ash, and Emrich (2014) have mapped the Baseline Resilience Indicators for Communities (BRIC) comprising six components (social, economic, housing and infrastructure, institutional, community, and environmental) for the USA using counties as a spatial unit. Schlör, Venghaus, and Hake (2018) used the Nexus City Index (NCI) to assess the resilience of 69 cities around the world. The NCI is made up of 5 indices: productivity index, infrastructure index, quality of life index, equity index and environmental sustainability index (Table 1). This type of analysis enables decision makers to compare urban or regional resilience. The component indicators - rather than the generic resilience index - help to provide guidance to policy makers to know where to invest at national or regional level (Cutter et al., 2014). It is also possible to study the temporal evolution of resilience indicators for a specific territory for evaluating the impact of policies on community resilience (Qin, Lin, & Fang, 2017). Despite these specific uses, we may wonder how useful this type of comparison is as the indicators are often calculated for large spatial units and do not help pinpoint hotspots where actions are needed. Furthermore, as resilience is so context-specific, we may wonder if resilience may be compared between different cities, regions or countries. By comparing rural and urban resilience, Cutter, Ash, and Emrich (2016) have showed for instance that “resilience cannot be approached using a ‘one-size-fits-most’ strategy given the variability in the primary drivers of disaster resilience at county scale” (page 1).

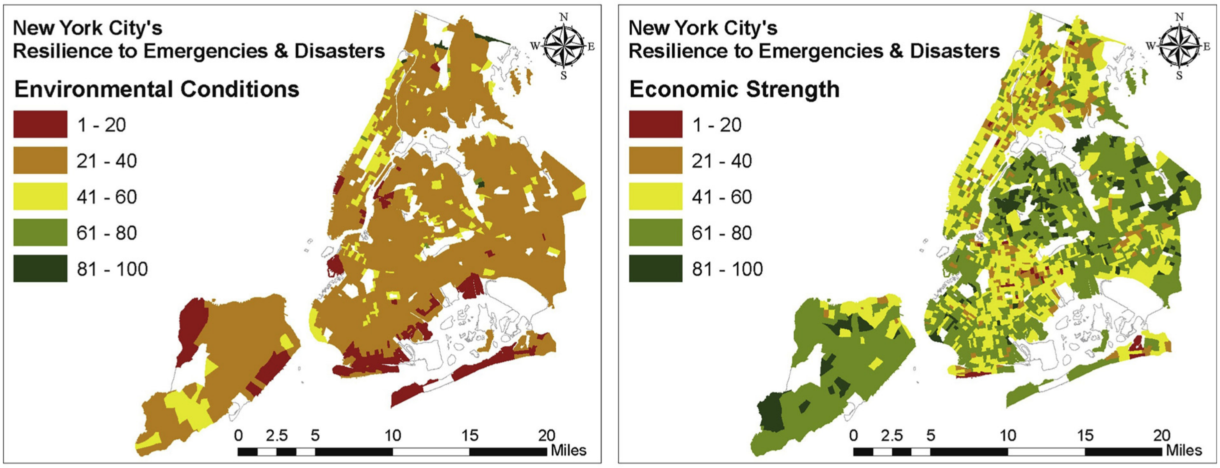
Among all the research papers identified, only a few propose methods for mapping urban resilience at the city scale (Kontokosta & Malik, 2018; Moghadas, Asadzadeh, Vafeidis, Fekete, & Kötter, 2019; Prashar, Shaw, & Takeuchi, 2012; Serre & Heinzlef, 2018; Zheng, Xin-Lu, Chen-Zhen, Mou, & Xiao-Jia, 2018). Kontokosta and Malik (2018) propose using 24 indicators to calculate scores for the following dimensions: social infrastructure and community connectivity, physical infrastructure, economic strength and environmental conditions. The Resilience to Emergencies and Disasters Index (REDI) has been mapped at the scale of New York City using census tracts as the spatial unit (Fig. 6). Maps are produced for each dimension making it possible to

Table 1
List of studies using a holistic resilience indicator to map resilience.

References	Indicators used	Outcomes
Cutter et al. (2010)	Resilience index, based on 5 dimensions: social, economic, institutional and infrastructure resilience, and community capital	Disaster resilience map of FEMA Region IV (south east of USA)
Prashar et al. (2012)	Climate Disaster Resilience Index (CDRI), calculated from five dimensions: physical, social, economic, institutional, and natural	Resilience map of Delhi (India) to climate-related disasters
Cutter et al. (2014)	Baseline resilience indicators for communities (BRIC), comprising 6 components (social, economic, housing and infrastructure, institutional, community, environmental)	Resilience map of USA
Joerin et al. (2014)	Climate Disaster Resilience Index (CDRI)	Climate disaster resilience map of Chennai (India)
Ross (2014)	Social resilience index Community capital index Economic resilience index Institutional resilience index Infrastructure resilience index Ecological resilience index	Resilience map of 75 US counties bordering the Gulf of Mexico
Lam et al. (2015)	Resilience Inference Measurement	Coastal resilience map of 25 countries located in the Caribbean region
Siebeneck et al. (2015)	Disaster Resilience of Place (DROP) model, from four dimensions: household assets, economic assets, community/response assets, and institutional assets	Disaster resilience map at the provincial level in Thailand
Shim and Kim (2015)	Resilience index with three dimensions : biophysical, built-environment and socioeconomic resilience	Resilience map of metropolitan areas of South Korea
Cai et al. (2016)	Resilience Inference Measurement (RIM)	Community resilience map of the Lower Mississippi River Basin
Suárez et al. (2016)	Urban resilience index, made of five factors : diversity, modularity, Tightness of feedbacks, social cohesion and innovation.	Resilience map of spanish province capitals
Chun, Chi, and Hwang (2017)	22 variables split in four categories: Human, community, economic and organizational	Social resilience map of Seoul (South Korea)
Kuscahyadi et al. (2017)	Natural disaster resilience based on infrastructure components of BRIC (Baseline resilience indicators for communities)	Natural disaster resilience map of infrastructures in Yogyakarta Province (Indonesia)
Kontokosta and Malik (2018)	Resilience to Emergencies and Disasters Index (REDI), made of 24 indicators for the following dimensions: social infrastructure and community connectivity, physical infrastructure, economic strength and environmental conditions	Resilience to Emergencies and Disasters map of New York City
Schlör et al. (2018)	Nexus City Index (NCI), made up of 5 indices: productivity index, infrastructure index, quality of life index, equity index and environmental sustainability index	Resilience map of 69 cities around the world
Serre and Heinzlef (2018)	Global resilience index with social, urban and technical indicators	Urban resilience map of Avignon (France)
Zheng et al. (2018)	Urban resilience index, with four dimensions : economic, social, ecological and infrastructure resilience	Urban resilience map of Beijing (China)
Moghadas et al. (2019)	Composite index based on six dimensions : social, economic, institutional, infrastructural, community capital and environmental	Urban flood resilience map of Tehran (Iran)



(a) Social Infrastructure and Community Connectivity (b) Physical Infrastructure



(c) Environmental Conditions (d) Economic Strength

Fig. 6. New York City categorical REDI scores – (a) social infrastructure, (b) physical infrastructure, (c) environmental conditions, and (d) economic strength (Source: Kontokosta & Malik, 2018).

Table 2
Examples of variables used to assess the physical resilience of housing.

Case study references	Housing resilience variables
Cutter et al. (2010)	Percentage of housing units that are not mobile homes % of housing units not built before 1970 and after 1994
Frazier et al. (2013)	Number of mobile homes Number of non-conforming homes in surge zones
Cutter et al. (2014)	% of housing units that are not manufactured homes % of housing units built prior to 1970 or after 2000
Yoon et al. (2016)	% of housing over 30 years old Housing density

identify the least resilient neighborhoods in detail. These neighborhoods are considered the least prepared to respond to and recover from future disasters. Here, potential limitations are: (1) the method is not dynamic and a time-dependent indicator would be needed, and (2) the interdependency between neighborhoods is not taken into account. According to the authors, a low-resilience neighborhood surrounded by areas of high resilience capacity should respond and recover better than a similar neighborhood surrounded by low-resilience areas.

Serre and Heinzlef (2018) have developed an urban resilience index based on the calculation of three urban, social and technical resilience indicators. These indicators are calculated at the neighborhood scale from a combination of several variables including “% of active people”, “age of population”, “highest diploma” or “vulnerable population” for social resilience; “critical infrastructure”, “urban density” and “aging of building” for urban resilience; “urban networks” and “aging of networks” for technical resilience. The method has been applied to the city of Avignon using the census tracts IRIS as spatial unit. This method is interesting even though the variables are not clearly defined and their choice is not clearly explained.

The choice of the variables to calculate holistic resilience indicators raises two questions. Firstly, several variables used for their calculation often express vulnerability rather than resilience. Secondly, if a variable enables to measure the resilience of an object in a specific context, this does not mean that it is valid everywhere else or for any hazard. To illustrate these two points, we have analyzed the variables proposed in the literature to assess the physical resilience of housing (Table 2). In the USA, Cutter, Burton, and Emrich (2010), 2014 and Frazier, Thompson, Dezzani, and Butsick (2013) suggest that housing resilience is a function of the number or percentage of mobile homes, also termed “not manufactured homes”. As justification for such a choice, Cutter et al. (2010) quote Cutter, Boruff, and Shirley (2003) who assumed that mobile homes are more vulnerable and easily destroyed during natural disasters. According to Cutter et al. (2003), this variable does not therefore depict resilience but vulnerability. Cutter et al. (2014) justify their choice from a study of the impact of tornados on mobile homes in the USA (Sutter & Simmons, 2010). This justification is based on one specific hazard and nothing is justified regarding the resilience of mobile home *vis-à-vis* other hazards. Frazier et al. (2013) do not provide any justification. This challenges the choice of this variable to assess resilience: are mobile homes less resilient than manufactured homes? This variable is also very specific to the American context where the number of people living in mobile homes is very high (about 6% of the total population[2]). We can thus wonder whether this variable would be relevant in other contexts.

A second type of variable proposed (Table 2) relates to the age of housing. Again, this variable is linked more to vulnerability than resilience. Moreover, variables linked to the age of housing may not be valid everywhere. In Paris for instance, buildings designed by Haussman in the late 19th century are considered more resilient to heat than new buildings as they allow for flexibility and are cooler during heatwaves (source: CyberArchi[3]).

Most of the holistic approaches are designed to assess the resilience of urban communities or territories to any kind of hazard or disturbance which can lead to a misunderstanding and inappropriate use of the concept of resilience. In order to assess resilience, we need to specify which system and which hazard or disturbance are of interest, namely the "resilience of what to what?" (Carpenter, Walker, Anderies, & Abel, 2001).

3.2.3.2. The resilience of what to what?. Besides holistic approaches, certain methodologies have been developed for specific urban objects, systems and/or for specific hazards. Lhomme, Serre, Diab, and Laganier (2013) for instance, proposed a method for spatially assessing the resilience of urban networks to flooding by analyzing their resistance, absorption and recovery capacity. Based on graph theory, resistance capacity is assessed by analyzing dysfunctions induced by damaged components and taking account of interdependencies. The absorption capacity is based on the calculation of network redundancy (Fig. 7) while the recovery capacity is calculated by analyzing accessibility between damaged networks and restoration centers.

Similar graph-based methodologies have been developed to assess the resilience of urban road networks under seismic hazards (Aydin, Duzgun, & Wenzel, 2018), the resilience of a metro system (Chopra, Dillon, Bilec, & Khanna, 2016; Zhang et al., 2018) or the resilience urban water distribution networks (Cimellaro, Tinebra, Renschler, & Fragiadakis, 2016).

Chen, Ferng, Wang, Wu, and Wang (2008), have mapped the resilience of Taiwanese communities to landslides and debris flow, using the Disaster Resilience Capacity index (DRC). The DRC index is based on the calculation of two other index: (1) the Community Preparedness for Disaster (CPD) which includes "emergency response capabilities", "warning system," and "reporting system" variables; (2) the Community Environmental Condition (CEC) which assess the hazard of landslide and debris flow. The DRC mainly focus on crisis time and thus do not depict the whole concept of resilience.

Cariolet, Colombert, Vuillet, and Diab (2018) developed a method to map the resilience of urban design to air pollution by calculating three capacities: the capacity of urban design to decrease emissions (Fig. 8); its capacity to decrease concentrations and its capacity to decrease exposure. This method has been applied to Greater Paris.

Bertilsson, Wiklund, Tebaldi, and Rezende (2018) proposed the Spatialized Urban Flood Resilience Index (S-FRESI) to map the urban flood resilience. The index is based on the calculation of three capacities: "(1) the capacity of maintaining resistance over a period of time (2) the capacity of the affected communities to recover from material losses and (3) the capacity of the drainage system to recover its functions and keep operating after the storm, guaranteeing basic conditions for urban services to return to normality" (Bertilsson et al., 2018 p 4).

Recently, Martins, da Silva, and Pinto (2019) have developed an indicator to map the resilience of districts regarding mobility. The indicator assess the possibility to transfer trips made in motorized modes to actives modes in case of a disruption of the mobility system.

In view of the definition of Meerow et al. (2016) described in the introduction, our review shows that inherent resilience maps do not consider "fully" the concept of resilience, as it do not map the capacity to adapt or to transform systems, but mainly represent the capacity of an urban system – or one of its sub-system – to maintain or rapidly return to desired functions.

4. Discussion

4.1. Mapping resilience: what contribution to disaster management?

We may wonder if mapping resilience contributes new elements to disaster management when compared with hazard and vulnerability mapping. Inherent resilience maps are useful in theory for pinpointing areas where actions are needed to improve urban resilience. However, Schipper and Langston (2015) have showed - by comparing different resilience measurement frameworks - that sector-specific indicators are more effective than holistic resilience indicators. More than a resilience score map, decision makers want to understand why some areas have low scores and how they can provide solutions for improving their resilience. In order to do this, maps need to be deconstructed to highlight the reasons for lower scores and devise appropriate actions together with the methods for developing these (Fig. 9).

In general, we observe that resilience is presented as a new conceptual risk management framework leading to more effective consideration of the time variable and systemic effects (Ehret et al., 2015). The relatively consensual nature of the indicators selected for the study of hazards (example: water levels or current velocity for a flood) greatly facilitates the mapping of its phenomena. We note that this is more complicated for vulnerability which can be defined as the propensity of a person, a building, a material infrastructure, but also an activity, an economic sector or, more broadly, a society or a territory to be damaged (Laganier, 2016). Vulnerability is often mapped using a subjective analytical approach (Heesen, Lorenz, Nagenborg, Wenzel, & Voss, 2014). In other words, vulnerability is assessed by adding up numerous variables chosen subjectively. This is also the case with inherent resilience which is why it appears complicated to map resilience and to understand such mapping (Table 3). The "porosity" between vulnerability and resilience mapping – in the sense that resilience is sometimes expressed as the opposite of vulnerability - adds more confusion.

According to Heesen et al. (2014), several aspects of vulnerability and resilience cannot be easily mapped, such as "specific forms of knowledge and interpretation, the processuality of vulnerability and resilience, the dynamics of social processes, the context of origin, the establishment of contingent interpretations, and so on" (Heesen et al., 2014, p74).

November (2006) had already pointed out that risk mapping (vulnerability x hazard) is fixed and does not represent the real spatiality of the risk nor its dynamics. This seems even more so with resilience partly due to the analytical approaches to creating such mapping.

4.2. A missing systemic approach

Most of the methods for mapping inherent resilience identified in this review are analytical and do not integrate the systemic property of

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[2] https://www.bbc.com/news/magazine-24135022

[3] http://www.cyberarchi.com/article/haussmann-un-modele-durable-22-02-2017-16161

Fig. 7. Orleans (France) road network redundancy analysis shows the weak redundancy of this network close to bridges (source: Lhomme et al., 2013).

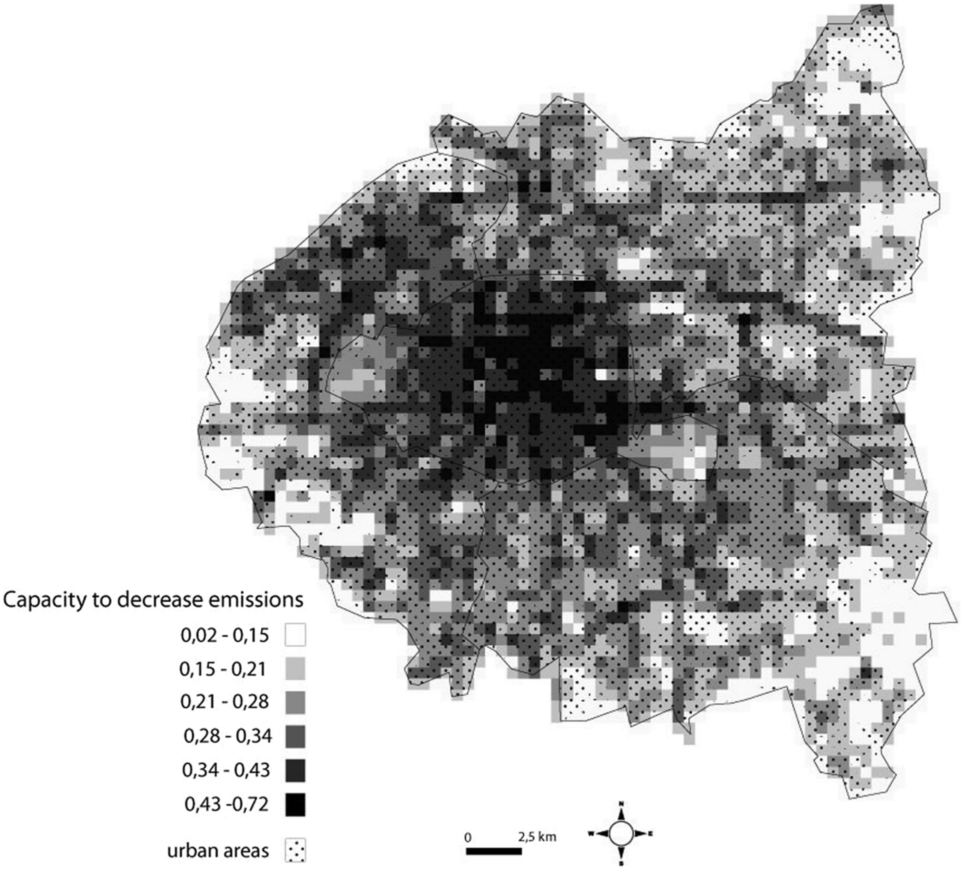

Fig. 8. Capacity of Greater Paris to decrease emissions (source: Cariolet et al., 2018).

resilience. According to Reghezza (2016), resilience is often considered aspatial due its systemic property. There is no doubt that the systemic character of resilience - generating a large number of possible connections and states, feedback loops as well as multiple parameters that are difficult to predict, describe or even identify – singularly complicates the production of general indicators and hence indisputable global maps. Nevertheless, the different aspects of resilience can be broken down (e.g.: various resilience factors, action plan components for a

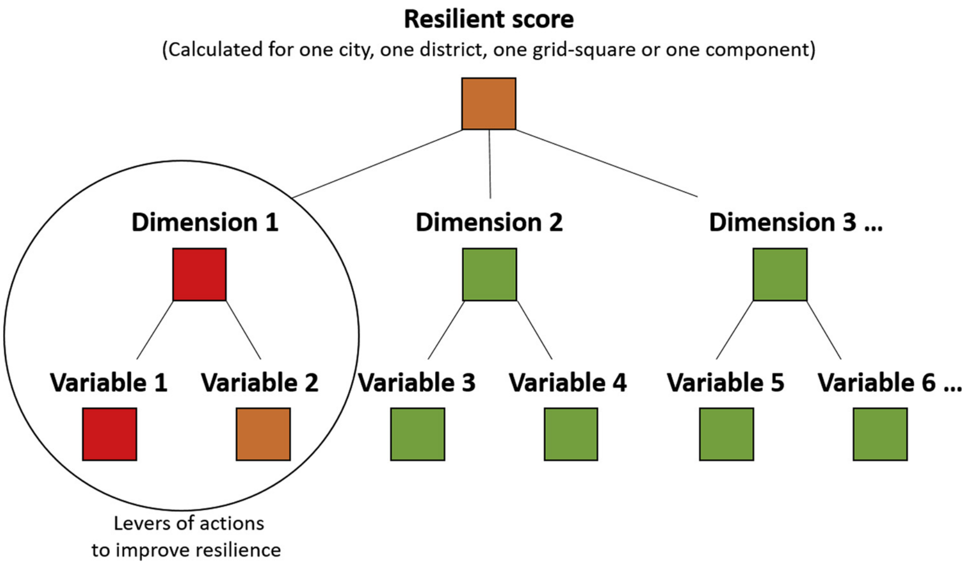

Fig. 9. Deconstruction of the resilience score for one geographical object (a city, a district, a grid-square or a component). In this case, the resilience score is high when green, average when orange and low when red. The low scores of variables 1 and 2 explain the resilience score. In order to improve resilience for the geographic object, variables 1 and 2 need to be improved (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 3
Difference between hazard, vulnerability and resilience mapping.

Hazard mapping	Vulnerability mapping	Resilience mapping
● Physical modelling or *in situ* measurements ● Few variables mapped	● Subjective analytical approach ● Infinity of variables can be mapped	*Adaptive resilience:* ● Dynamic approach ● Few variables can be mapped (sectorial approach) *Inherent resilience:* ● Subjective analytical approach to measuring a dynamic capacity ● Infinity of variables can be mapped

more effective relaunch of operations, planned functioning of urban systems in degraded mode, etc.) into as many maps useful for implementing actions aimed at improving urban resilience. Along with vulnerability-based analytical mapping elements, maps used for resilience studies potentially provide richer decision support but are also harder to interpret as the user has to think about their systemic implications.

Recently, Mahmoud and Chulahwat (2018) managed to produce resilience maps of a fictional city (Gotham City) using a systemic approach. Using a grid-based approach, the authors developed an integrative model that analyses 6 lifeline systems (i.e., housing, water, power, transportation, communication and health) and their interdependencies (Fig. 10). The resulting resilience maps take account of systemic dynamics (Fig. 11). Other studies attempt to integrate systemic properties of resilience by using graph theory (Bozza, Asprone, Parisi, & Manfredi, 2017a; Bozza, Asprone, & Manfredi, 2017b; Koren, Kilar, & Rus, 2017) but seems far from being operational.

4.3. Scale, granularity and data availability

Most of the methods developed to map community resilience have been applied at continental (Lam, Qiang, Arenas, Brito, & Liu, 2015; Ross, 2014), national (Cutter et al., 2014; Kammouh, Dervishaj, & Cimellaro, 2018; Siebeneck, Arlikatti, & Andrew, 2015; Suárez, Gómez-Baggethun, Benayas, & Tilbury, 2016), or regional scale (Cai, Lam, Qiang, & Li, 2016; Cutter et al., 2010; Joerin, Shaw, Takeuchi, & Krishnamurthy, 2014; Kuscahyadi, Irwan, & Riqqi, 2017) using spatial units such as countries (Sherrieb, Norris, & Galea, 2010), regions (Siebeneck et al., 2015; Suárez et al., 2016), counties (Cutter et al., 2010 and Cutter et al., 2014) or city administrative boundaries (Joerin et al., 2014; Kuscahyadi et al., 2017; Miles & Chang, 2011; Schlör et al., 2018; Tyler et al., 2016; Yoon, Kang, & Bordy, 2016). As pointed out by Kontokosta and Malik (2018), "most of these models either lack data at the spatial granularity needed to adequately represent urban neighborhoods – resulting in several studies that instead use counties or other large administrative divisions" (page 273). Recently, Cai et al. (2016) managed to use a fine spatial granularity at a regional scale using census blocks. However, only a few recent papers have mapped urban resilience specifically, i.e., on a city scale. Census tracts are the most common spatial unit used at this scale (Kontokosta & Malik, 2018; Serre & Heinzlef, 2018) but they do not always provide a detailed understanding of the spatial distribution of resilience indicators in an urban area. Researchers appear forced to choose or dismiss certain indicators because of data availability. Furthermore, maps based on aggregation are affected by the Modifiable Areal Unit Problem (MAUP). The choice of spatial units and their scale may affect the results (here the score of the resilience index), which may lead to spurious inequality between units. This can be worsened when similar spatial units are grouped (Larsen, 2000). Such maps are thus dependant on the mapmaker's choices, and we can wonder how sensitive the fuzzy concept of resilience is to these choices. MAUP sensitivity analysis should be performed systematically in order to validate such results.

When data is available, it is possible to map the resilience capacity of the components of a system studied (Aydin et al., 2018; Cimellaro et al., 2016; Chopra et al., 2016; Lhomme et al., 2013; Zhang et al., 2018). In France, the national reference system of vulnerability to flooding (*référentiel national de vulnérabilité aux inondations*) maps recovery capacity (IAU, 2017). These maps are prepared by overlaying the hazard, the areas of electrical fragility and the components of the territories that participate in the recovery of a given territory (nurseries, hospitals, institutions schools, metro stations etc.). This type of mapping has the advantage of providing more information on resilience than maps which use surface elements only. Nevertheless, in dense territories, the maps are often overloaded with elements and not very legible.

Finally, other researchers use grid-based approaches in order to

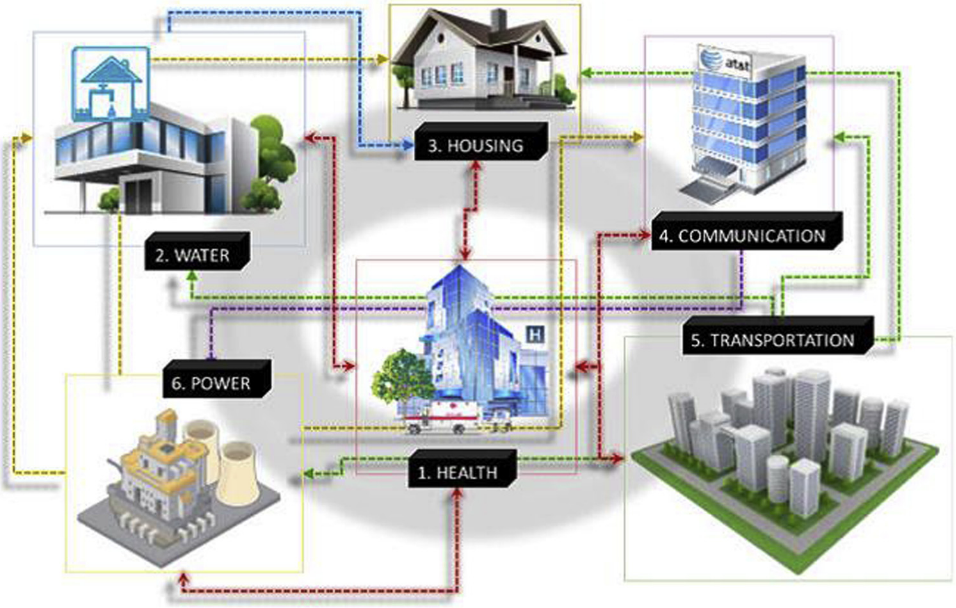

Fig. 10. Interdependencies between lifeline systems in the study of the resilience of Gotham City (Mahmoud & Chulahwat, 2018).

gather data with different granularities (Cariolet et al., 2018; Renschler et al., 2010). Grid-based approaches are particularly interesting when the smallest administrative spatial unit is too big for the territory studied.

4.4. Validation of the indicators

One major limitation of the approaches presented to map inherent resilience is the absence of methods to validate the reliability of the proposed indicators (Asadzadeh, Kötter, Salehi, & Birkmann, 2017). This validation can be performed only by comparing results with actual disaster event outcomes using proxies that demonstrate the resilience of a system or territory, which shows the difference between normal and crisis situations.

Kontokosta and Malik (2018) proposed a method to validate the REDI index by analyzing 311 service requests before, during and after Hurricane Sandy in New York City. According to the authors, 311 requests is a good proxy for measuring the neighborhood activity and makes it possible to compare recovery time between neighborhoods. In their conclusions, Kontokosta and Malik (2018) highlight the need for more proxies in order to validate such resilience indicators.

Links between adaptive resilience mapping and inherent resilience mapping need to be made by researchers. Indeed, adaptive resilience mapping provides precious information for validating variables and indicators used to map inherent resilience.

Following Hurricane Sandy in New York, mapping has been developed to characterize the redundancy of technical networks from a spatial perspective. Regarding telecommunications for instance, it appeared that buildings that had multiple telecommunication providers were more resilient - in term of telecommunications - as residents and businesses were able to switch to those providers that restored service first (The City of New York, 2013; page 168).

4.5. Perspectives

Top-down approaches make it possible to quantify and map inherent resilience. Variables and indicators proposed vary from one researcher to another (see for instance Table 2) and there is currently a tendency to propose standardized resilience indicators (e.g., ISO 37123 under development). While standardized indicators will make it possible to compare the resilience scores of different urban areas, this process is not without risk. Indeed it is important to challenge the validity of certain variables or indicators in specific contexts or parts of the world. The examples listed in Table 2 are revealing. Resilience is context-dependent and cannot be measured everywhere with the same variables and indicators. Furthermore, holistic standardized resilience

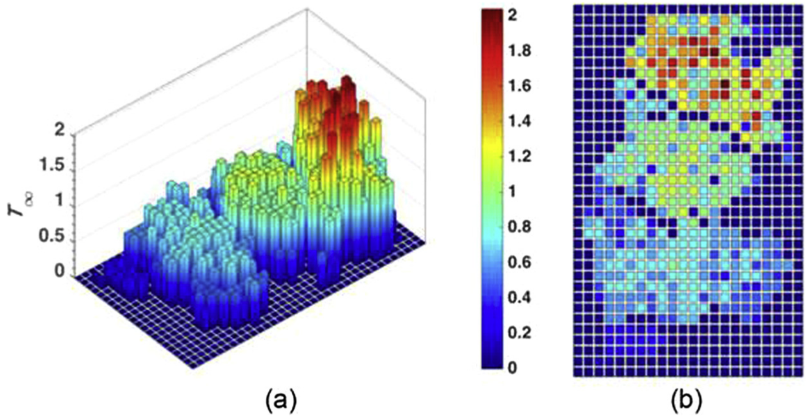

Fig. 11. Time to stabilization ($T\infty$) values obtained for Housing lifeline in Gotham City (Source: Mahmoud & Chulahwat, 2018).

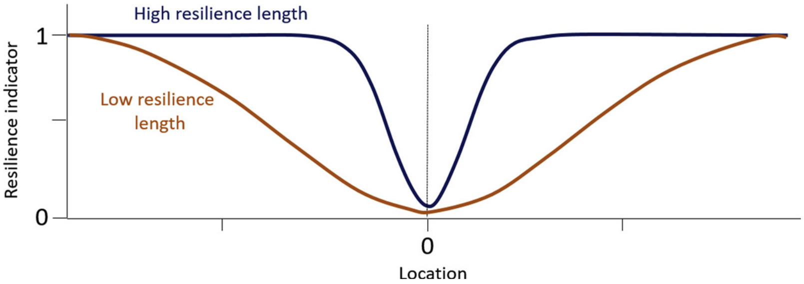

Fig. 12. Recovery length is the distance that a system must be from a localized disturbance for it to recover its normal functioning. In resilient systems, the distance of disfunctionning is lower than in non-resilient systems (adapted from Dai et al., 2013).

indicators do not take account of the relative nature of resilience ("resilience of what to what"). This may lead to maladaptation and further research needs to be conducted to develop context-specific indicators. One possible solution could be to find ways to obtain quantified and spatialized results from bottom-up approaches by using a combination of mental maps and fuzzy approaches. Another possibility could be to develop methodologies that combine bottom-up and top-down approaches. Variables and indicators should be chosen and even developed by local stakeholders and experts but once again, their calculation will be dependent on the availability of data. Other methods may propose semi-quantitative indicators such as the one proposed by Tabibian and Rezapour (2015), where local experts assign scores for several variables using a 5 level scoring system (very low, low, medium, high, very high) and focusing on several areas of a city. Finally, systemic approaches need to be developed to produce dynamic and integrative maps, such as that proposed by Mahmoud and Chulahwat (2018).

While data availability is a big concern when quantifying inherent resilience, big data and open data could potentially open new perspectives for the development of new resilience indicators as suggested by Kontokosta and Malik (2018). Real time data could also improve the integration of systemic approaches within GIS and interactive maps.

Web mapping should also help improve urban resilience to disasters in the future. According to Tate, Burton, Berry, Emrich, and Cutter (2011), web mapping enables the development of applications that are dynamic, and accessible for everyone. Furthermore, it enables disaster managers to spend more time creating effective planning and strategies instead of collecting data and creating maps. Based on collective and public participation, web mapping is perhaps a key mapping strategy for dealing with urban resilience as it enables to access to large scale data. During recent disaster events (South-East Asian tsunami in 2004, Hurricane Katrina in New Orleans in 2005, Haiti earthquake in 2010 etc.), Volunteered Geographic Information (VGI) have been used and proved to be useful during disaster management (Roche, Propeck-Zimmermann, & Mericskay, 2011). However, future researches need to be conducted to analyses potential miss-use and associated risks regarding the use of web mapping for mapping or improving resilience.

The review shows that it is currently not possible to map the resilience of a city entirely because the level of complexity is too great. We suggest that researchers first need to focus on the resilience of sub-systems and hazards instead of trying to be holistic.

Researchers working on urban resilience could once again be influenced by ecological resilience in the future. Ecology proposes new concepts and ways of measuring and mapping the resilience of ecosystems which could be applied to urban systems. Among them, the concept of recovery length is promising as it deals directly with the spatial dimension of resilience. Dai, Korolev, and Gore (2013) define the concept of recovery length as the distance that a system must be from a localized disturbance for it to recover its normal functioning. In resilient systems, the distance of disfunctionning is less than in non-resilient systems (Fig. 12). This concept could help in comparing the resilience of different complex systems or even predicting their future transitions – or tipping points.

5. Conclusions

This paper reviewed research literature concerning the ways of mapping urban resilience. The review results revealed that adaptive resilience is mapped after a disaster for specific elements or sub-systems, through the measure of recovery. Inherent resilience is generally mapped using indicators based on a top-down approach. Resilience maps do not consider "fully" the concept of resilience, as it does not map the capacity to adapt or to transform systems. Most of the methods for mapping inherent resilience are analytical and do not depict the systemic property of resilience. Also results show that the frontier between resilience and vulnerability maps is fuzzy and narrow.

The review revealed several challenges in mapping urban resilience. Resilience being context-dependent, it is hard to find relevant variables or indicators that are practical for every city. Also, there is a need to develop methods and to find relevant proxies in order to validate these indicators and variables.

We suggest that research needs to be developed based around intermediate or hybrid methods (i.e., mixing top-down and bottom-up approaches) and focusing on the resilience of sub-systems as it is still not possible to map urban resilience totally as the complexity is too great. Ways of integrating systemic approaches into urban resilience mapping need to be developed too. Finally, as maps are mainly meant to be used by decision makers, such methods should be co-created along with them.

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