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Mapping urban resilience to disasters - review

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Mapping urban resilience to disasters – a review

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.

Keywords: urban resilience, map, GIS, resilience indicators

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 and 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 T.J., 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

51 paradigm (Landau and Diab, 2016). The term resilience has been defined in many ways as already
52 discussed elsewhere (Cutter *et al.*, 2008; Alexander, 2013; Meerow *et al.*, 2016). Regarding urban
53 resilience more specifically, Meerow *et al.* (2016) note that the concept is also characterized by
54 conceptual tensions and they propose a broad definition based on a review of literature:

55
56 “Urban resilience refers to the ability of an urban system-and all its constituent socio-ecological and
57 socio-technical networks across temporal and spatial scales-to maintain or rapidly return to desired
58 functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit
59 current or future adaptive capacity.” (Meerow *et al.*, 2016; page 39)

60
61 This definition highlights the fact that resilience has a systemic property (Reghezza, 2016) and implies
62 greater consideration of the time variable.

63 Besides urban resilience, [North American](#) researchers often refer to community resilience to study
64 resilience at the community level and this approach incorporates an important social component. As
65 community is considered a system of interconnected systems (Cutter, 2016) we may consider
66 community resilience in urban areas as similar to urban resilience (and this approach will be taken in
67 this article).

68

69 **1.2. Objectives of the review**

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

77

78 **2. Methodology**

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

88
89 After duplicated studies were removed, remaining articles were screened based on title and
90 abstracts. At this step, articles were selected based on the following inclusion and exclusion criteria:

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

95
96 The remaining articles were screened based on full-texts and figures. Articles with at least one map
97 linked with the concept of resilience were selected (fig. 1).

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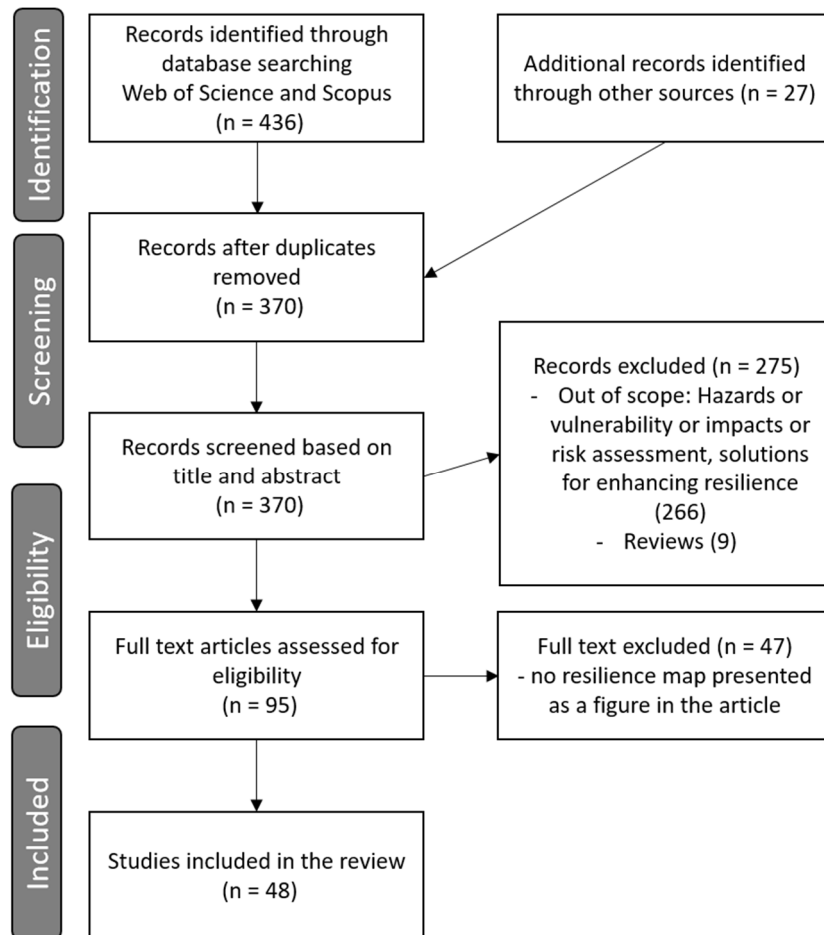


Fig. 1. Systematic review summary

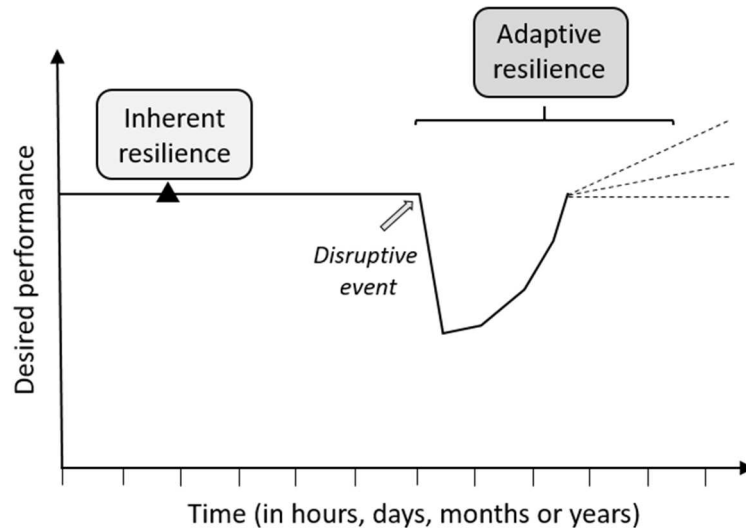
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The 48 papers were read in full and then categorized and analyzed by the first author. This was done following a methodology developed by all three authors, which relies on a descriptive analysis of the methods developed to produce resilience maps 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?

110 3. Results

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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. Tierney (2007), Rose (2004) and Cutter (2016) 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, 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.



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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.

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2.1 . Mapping adaptive resilience

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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 sub-systems.

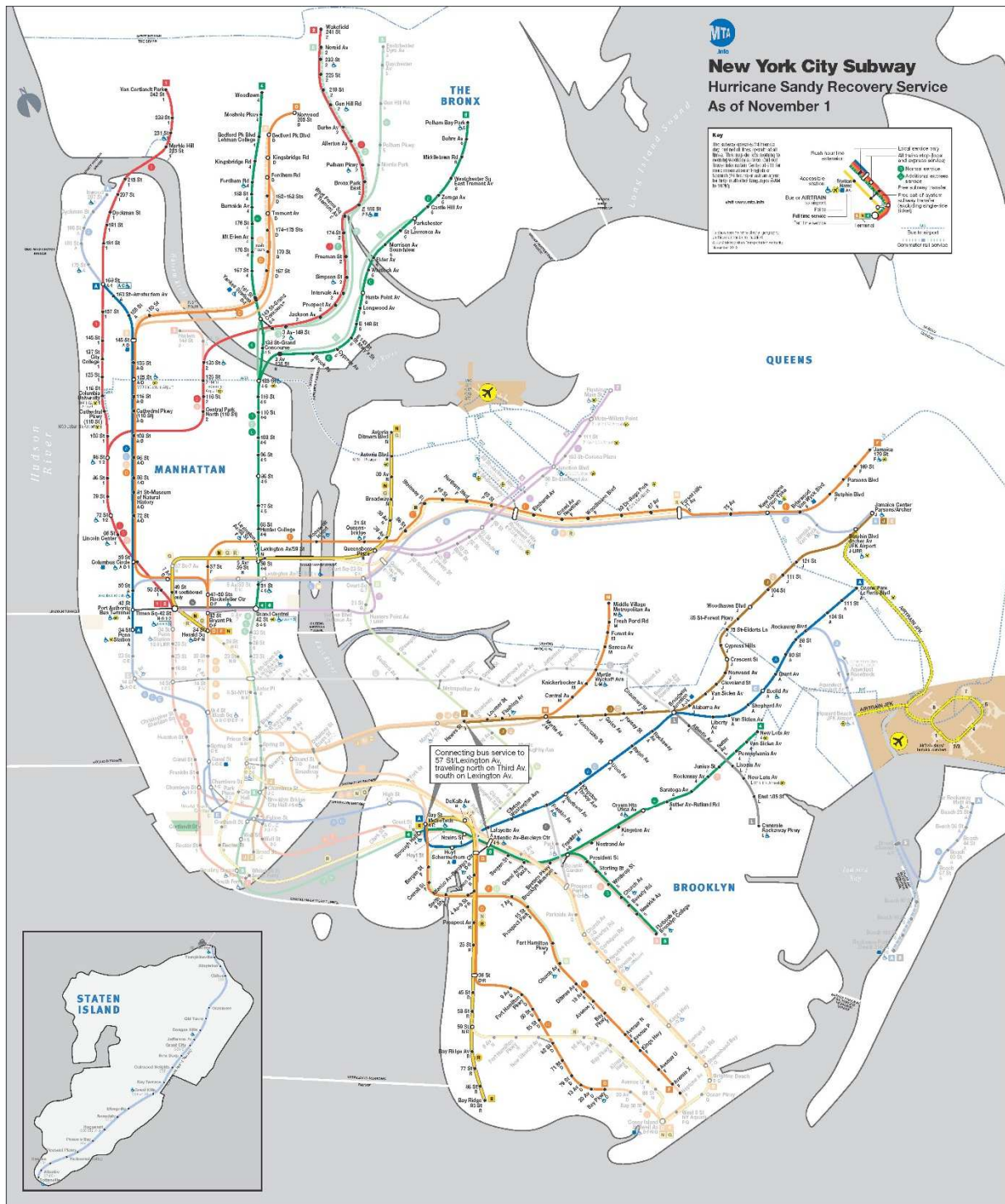
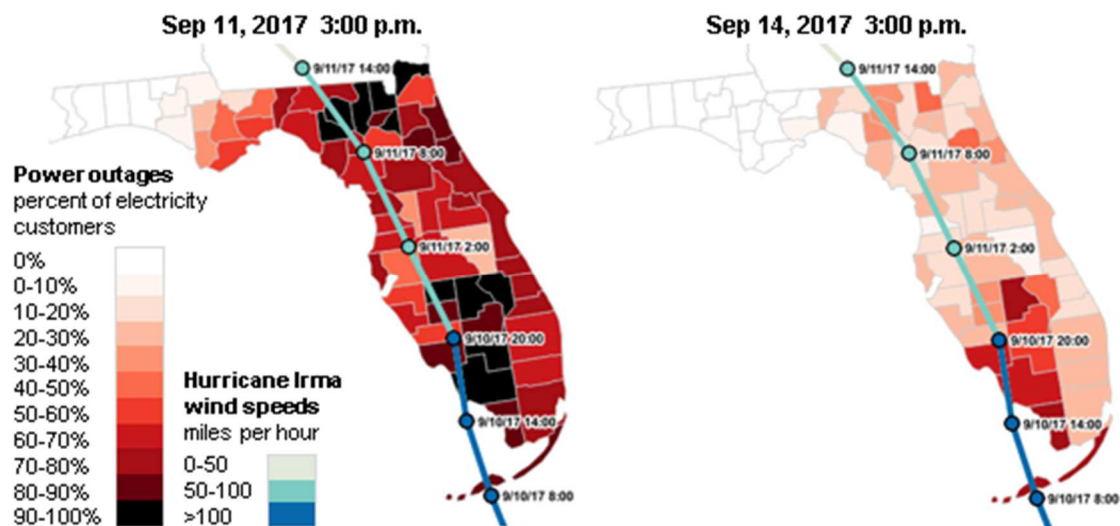


Fig. 3. Recovery of the New York City subway after hurricane Sandy, on the 1st of November 2012 (source: MTA)

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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.

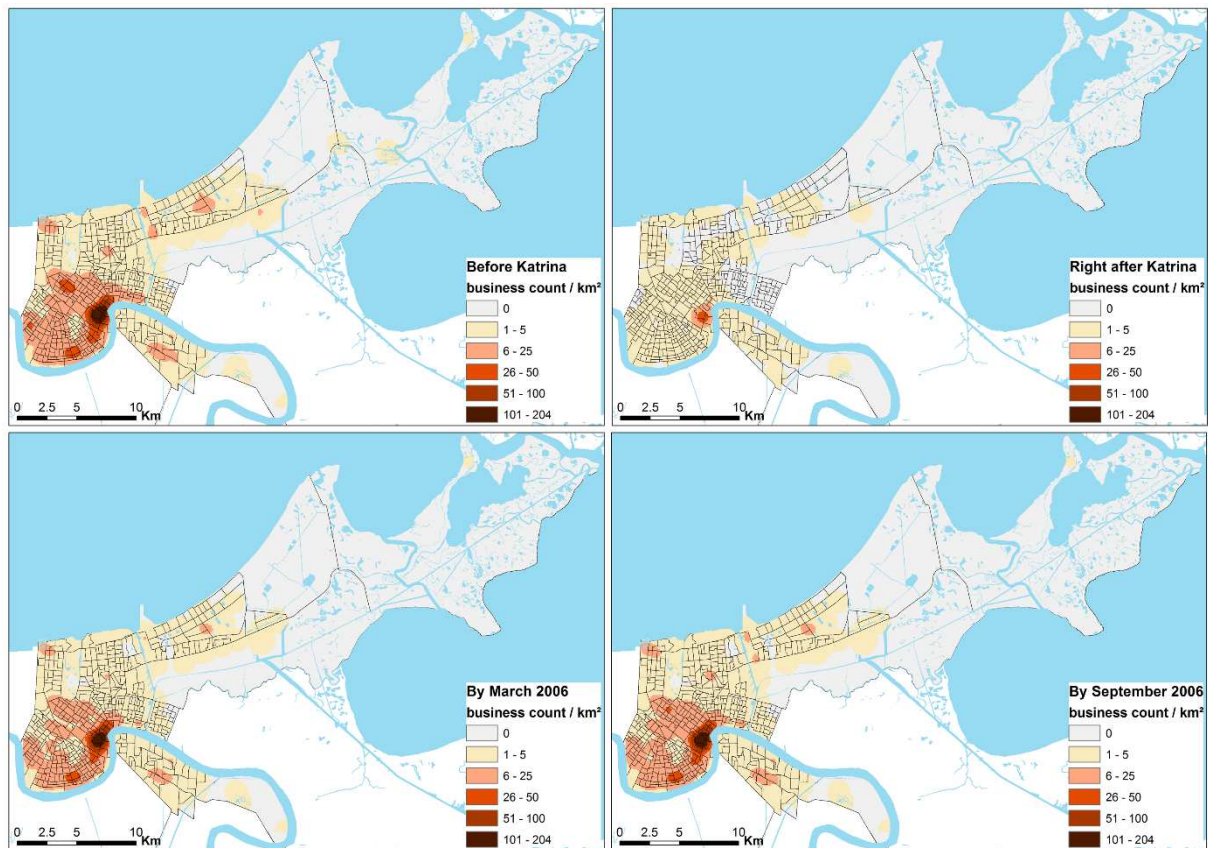


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Fig. 4. Florida power outages by county after Hurricane Irma between the 11th and 14th of September 2017. The hurricane crossed Florida during the 10th and 11th of September 2017. Source: U.S. Energy Information Administration based on data from the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

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 *et al.* (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.



172
173 *Fig. 5. Density maps of opened businesses in New Orleans before, during and after hurricane Katrina*
174 *(Lam et al., 2012)*
175

176 Contreras *et al.* (2018) have mapped the evolution of recovery of L’Aquila (Italy) following the
177 earthquake of 2009, based on the calculation of a recovery index for the years 2010, 2012, 2014 and
178 2016. The recovery index is based on building condition and building use evaluation. According to the
179 authors, the recovery index is useful for identifying spatial pattern – such as hot spots - of the
180 recovery process.

181
182 This type of experience/feedback-based mapping focus mainly on the post-disaster recovery process
183 of specific elements or sub-systems of what constitutes urban resilience, but do not depict the
184 possible changes of trajectories for a city. However, what is actually mapped at a given moment
185 might not depict a bounce-back outcome, but might be a temporary unstable state.

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187 **2.2. Mapping inherent resilience**

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189 2.2.1. Bottom-up and Top-down approach

190
191 Cutter (2016) distinguishes two kinds of methodological approaches to assess the resilience of a
192 community: bottom up and top down. Bottom-up approaches are often qualitative and measure the
193 resilience of institutions or governance structures. According to Cutter (2016), “the ability to
194 compare across places” using bottom-up approaches “is difficult because of the variability in data,
195 and the different contexts and meanings of resilience” (page 745). For these reasons, and also
196 because most of the data used in these methods are not available spatially or even mappable, this
197 kind of approach does not enable the production of maps. Many cities around the world are
198 currently using bottom-up approaches, such as the city resilience index developed by Arup and used
199 in the 100 Resilient Cities network (Spaans and Waterhout, 2017), or the urban resilience index

200 developed by the International Environment and Disaster Management Laboratory in Kyoto (Kabir *et al.*, 2018).
201

202
203 Top-down approaches use available data and quantitative methods for calculating resilience
204 indicators for specific units of analysis (district, region, state, etc.) depending on the scale of a case
205 study and on data. Within the resilience community, they are often expressed by a score from 0 to 1.
206 According to Cutter (2016), this type of approach can be used to examine spatial variability. Most
207 inherent resilience maps are produced using a top-down approach. Indeed, map producers usually
208 use global indicators as it is not generally possible to factor in the real complexity of urban resilience.
209

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

214 215 2.2.2. Using the opposite of vulnerability to map resilience

216
217 The concept of resilience is sometimes considered the opposite of vulnerability (Folke *et al.*, 2002;
218 Gallopin, 2006; Bates *et al.*, 2014), as vulnerable territories tend to be less resilient (Bergstrand *et al.*,
219 2015). This helped give resilience an operational and understandable definition, and the positive
220 connotation of resilience - unlike vulnerability – facilitated its applicability (Reghezza-Zitt *et al.*,
221 2012). According to this principle, certain mapping methods consider that low vulnerability is equal
222 to high resilience and thus use traditional vulnerability indicators to devise resilience indicators (Van
223 Zandt *et al.*, 2012; Jabareen, 2013; Highfield *et al.*, 2014). Other approaches such as the *Resilience*
224 *Atlas*¹ do not even consider the “flip-side” of vulnerability, but use exposure and vulnerability
225 analysis directly to produce what they call resilience maps. According to Reghezza-Zitt *et al.* (2012), it
226 is not always possible to oppose resilience and vulnerability as a vulnerable system may be resilient
227 and vice-versa. History shows that cities are vulnerable to natural hazards but often resilient, as very
228 few cities have actually disappeared over the centuries (Vale and Campanella, 2005). Reghezza-Zitt *et al.*
229 *et al.* (2012) go further by arguing that “there can only be resilience if an impact and a disruption occur,
230 which analytically, implies vulnerability”. Therefore, resilience cannot be measured by using the
231 opposite of vulnerability. Another way of quantifying resilience, namely the capacity approach, has
232 helped operationalizing the concept.

233 234 2.2.3. The capacity approach

235
236 The variables used to build resilience indicators are often based on resilience principles (or
237 properties), which are considered the general attributes that a resilience system should possess
238 (Sharifi and Yamagata, 2016) and they have helped researchers to develop resilience indicators in
239 different domains such as ecology, psychology, urban sciences, etc. These principles are numerous -
240 robustness, stability, flexibility, redundancy, resourcefulness, diversity, independence, self-
241 organization, agility, omnivory, homeostasis, high flux, buffering, flatness, etc. – and their definition
242 has already been discussed elsewhere (Biggs *et al.*, 2015; Touili and Vanderlinden, 2015; Sharifi and
243 Yamagata, 2016 ; Wardekker, 2018). What is interesting here is that these principles can be applied
244 to any system, making it a powerful approach.

245
246 The seminal paper written by Bruneau *et al.* (2003) proposed a framework for assessing community
247 resilience by evaluating four principles that define the capacity of communities to be resilient:
248 robustness, redundancy, resourcefulness and rapidity. According to the authors, these principles
249 need to be quantified around four technical, organizational, social and economic dimensions. This

¹ <https://www.resilienceatlas.org>

250 work helped operationalizing the concept of resilience through the notion of capacity and its
251 associated principles.
252 In 2007, Foster proposed a Resilience Capacity Index (RCI) which was calculated at regional level and
253 then mapped at national level. The RCI is based on the calculation of 12 indicators, including
254 economic, demographic and social connectivity factors. This method has been applied in the USA
255 (Foster, 2007) and in Slovakia (Hudec *et al.*, 2018). The capacity approach has inspired many other
256 researchers (Cutter, 2016) but only a few methods propose maps as outputs. Among these, we have
257 especially identified holistic approaches that measure the resilience of a community or territory to
258 any kind of hazard along different dimensions (i.e., technical, social, economic, etc.).

259 2.2.3.1. Holistic resilience indicators

261
262 [Studies using a holistic approach to map resilience of a territory are listed in tab. 1.](#) Many identified
263 holistic approaches use spatial units which are larger than cities. Although these approaches do not
264 map urban resilience specifically – because of their broad granularity – they are worthwhile analyzing
265 for the purposes of this review as they are based on variables that could be used on an urban scale.
266 [For instance](#), Cutter *et al.* (2014) have mapped the Baseline Resilience Indicators for Communities
267 (BRIC) comprising six components (social, economic, housing and infrastructure, institutional,
268 community, and environmental) for the USA using counties as a spatial unit. Schlör *et al.* (2018) used
269 the Nexus City Index (NCI) to assess the resilience of 69 cities around the world. The NCI is made up
270 of 5 indices: productivity index, infrastructure index, quality of life index, equity index and
271 environmental sustainability index ([tab. 1](#)). This type of analysis enables decision makers to compare
272 urban or regional resilience. The component indicators - rather than the generic resilience index -
273 help to provide guidance to policy makers to know where to invest at national or regional level
274 (Cutter *et al.*, 2014). It is also possible to study the temporal evolution of resilience indicators for a
275 specific territory for evaluating the impact of policies on community resilience (Qin *et al.*, 2017).
276 Despite these specific uses, we may wonder how useful this type of comparison is as the indicators
277 are often calculated for large spatial units and do not help pinpoint hotspots where actions are
278 needed. Furthermore, as resilience is so context-specific, we may wonder if resilience may be
279 compared between different cities, regions or countries. By comparing rural and urban resilience,
280 Cutter *et al.* (2016) have showed for instance that “resilience cannot be approached using a ‘one-
281 size-fits-most’ strategy given the variability in the primary drivers of disaster resilience at county
282 scale” (page 1).

283
284 Among all the research papers identified, only a few propose methods for mapping urban resilience
285 at the city scale (Prashar *et al.*, 2012; Kontokosta and Malik, 2018; Serre and Heinzlef, 2018; Zheng *et al.*,
286 2018; Moghadas *et al.*, 2019). Kontokosta and Malik (2018) propose using 24 indicators to
287 calculate scores for the following dimensions: social infrastructure and community connectivity,
288 physical infrastructure, economic strength and environmental conditions. The Resilience to
289 Emergencies and Disasters Index (REDI) has been mapped at the scale of New York City using census
290 [tracts](#) as the spatial unit (Fig. 6). Maps are produced for each dimension making it possible to identify
291 the least resilient neighborhoods in detail. These neighborhoods are considered the least prepared to
292 respond to and recover from future disasters. Here, potential limitations are: (1) the method is not
293 dynamic and a time-dependent indicator would be needed, and (2) the interdependency between
294 neighborhoods is not taken into account. According to the authors, a low-resilience neighborhood
295 surrounded by areas of high resilience capacity should respond and recover better than a similar
296 neighborhood surrounded by low-resilience areas.

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

References	Indicators used	Outcomes
Cutter <i>et al.</i> (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 <i>et al.</i> (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 <i>et al.</i> (2014)	Baseline resilience indicators for communities (BRIC), comprising 6 components (social, economic, housing and infrastructure, institutional, community, environmental)	Resilience map of USA
Joerin <i>et al.</i> (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 <i>et al.</i> (2015)	Resilience Inference Measurement	Coastal resilience map of 25 countries located in the Caribbean region
Siebeneck <i>et al.</i> (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 <i>et al.</i> (2016)	Resilience Inference Measurement (RIM)	Community resilience map of the Lower Mississippi River Basin
Suarez <i>et al.</i> (2016)	Urban resilience index, made of five factors : diversity, modularity, Tightness of feedbacks, social cohesion and innovation.	Resilience map of spanish province capitals
Chun <i>et al.</i> (2017)	22 variables split in four categories: Human, community, economic and organizational	Social resilience map of Seoul (South Korea)
Kuscahyadi <i>et al.</i> (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 <i>et al.</i> (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 <i>et al.</i> (2018)	Urban resilience index, with four dimensions : economic, social, ecological and infrastructure resilience	Urban resilience map of Beijing (China)
Moghadas <i>et al.</i> (2019)	Composite index based on six dimensions : social, economic, institutional, infrastructural, community capital and environmental	Urban flood resilience map of Tehran (Iran)

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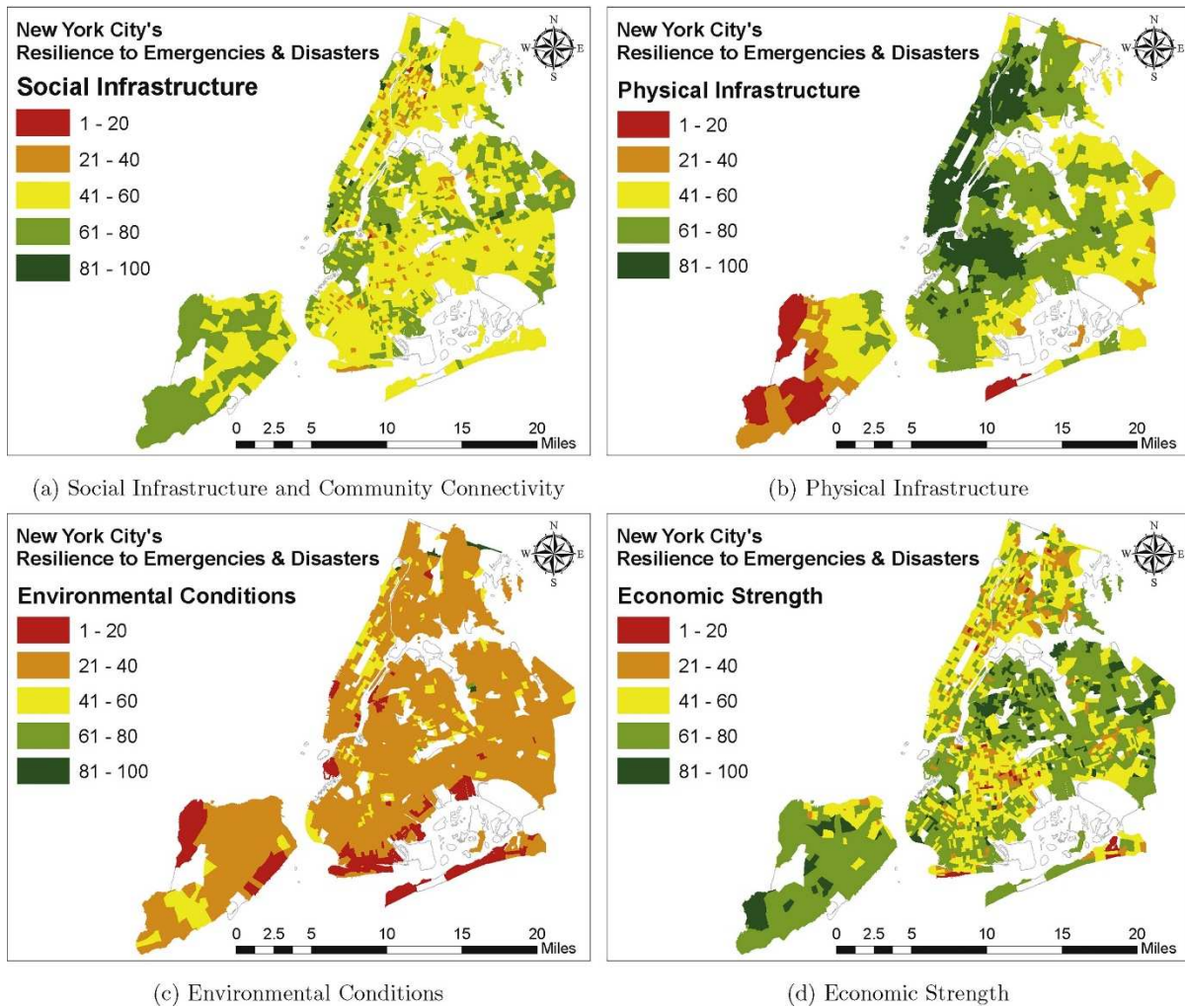


Fig. 6. New York City categorical REDI scores – (a) social infrastructure, (b) physical infrastructure, (c) environmental conditions, and (d) economic strength (Source: Kontokosta and Malik, 2018)

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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.

320

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 (tab. 2). In the USA, Cutter *et al.* (2010; 2014) and Frazier *et al.* (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 *et al.* (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)

330

331 justify their choice from a study of the impact of tornados on mobile homes in the USA (Sutter and
 332 Simmons, 2010). This justification is based on one specific hazard and nothing is justified regarding
 333 the resilience of mobile home *vis-à-vis* other hazards. Frazier *et al.* (2013) do not provide any
 334 justification. This challenges the choice of this variable to assess resilience: are mobile homes less
 335 resilient than manufactured homes? This variable is also very specific to the American context where
 336 the number of people living in mobile homes is very high (about 6% of the total population²). We can
 337 thus wonder whether this variable would be relevant in other contexts.

338 A second type of variable proposed (tab. 2) relates to the age of housing. Again, this variable is linked
 339 more to vulnerability than resilience. Moreover, variables linked to the age of housing may not be
 340 valid everywhere. In Paris for instance, buildings designed by Haussman in the late 19th century are
 341 considered more resilient to heat than new buildings as they allow for flexibility and are cooler
 342 during heatwaves (source: CyberArchi³).

343
 344 *Tab. 2. Examples of variables used to assess the physical resilience of housing*

Case study references	Housing resilience variables
Cutter <i>et al.</i> , 2010	Percentage of housing units that are not mobile homes % of housing units not built before 1970 and after 1994
Frazier <i>et al.</i> , 2013	Number of mobile homes Number of non-conforming homes in surge zones
Cutter <i>et al.</i> , 2014	% of housing units that are not manufactured homes % of housing units built prior to 1970 or after 2000
Yoon <i>et al.</i> , 2015	% of housing over 30 years old Housing density

345
 346 Most of the holistic approaches are designed to assess the resilience of urban communities or
 347 territories to any kind of hazard or disturbance which can lead to a misunderstanding and
 348 inappropriate use of the concept of resilience. In order to assess resilience, we need to specify which
 349 system and which hazard or disturbance are of interest, namely the “resilience of what to what?”
 350 (Carpenter *et al.*, 2011).

351
 352 *2.2.3.2. The resilience of what to what?*

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 354 Besides holistic approaches, certain methodologies have been developed for specific urban objects,
 355 systems and/or for specific hazards. Lhomme *et al.* (2013) for instance, proposed a method for
 356 spatially assessing the resilience of urban networks to flooding by analyzing their resistance,
 357 absorption and recovery capacity. Based on graph theory, resistance capacity is assessed by analyzing
 358 dysfunctions induced by damaged components and taking account of interdependencies. The
 359 absorption capacity is based on the calculation of network redundancy (fig. 7) while the recovery
 360 capacity is calculated by analyzing accessibility between damaged networks and restoration centers.
 361

² <https://www.bbc.com/news/magazine-24135022>

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



362
363 *Fig. 7. Orleans (France) road network redundancy analysis shows the weak redundancy of this*
364 *network close to bridges (source: Lhomme et al., 2013)*
365

366 Similar graph-based methodologies have been developed to assess the resilience of urban road
367 networks under seismic hazards (Aydin *et al.*, 2018), the resilience of a metro system (Chopra *et al.*,
368 2016; Zhang *et al.*, 2018) or the resilience urban water distribution networks (Cimellaro *et al.*, 2015).
369

370 Chen *et al.* (2008), have mapped the resilience of Taiwanese communities to landslides and debris
371 flow, using the Disaster Resilience Capacity index (DRC). The DRC index is based on the calculation of
372 two other index: (1) the Community Preparedness for Disaster (CPD) which includes “emergency
373 response capabilities”, “warning system,” and “reporting system” variables; (2) the Community
374 Environmental Condition (CEC) which assess the hazard of landslide and debris flow. The DRC mainly
375 focus on crisis time and thus do not depict the whole concept of resilience.
376

377 Cariolet *et al.* (2018) developed a method to map the resilience of urban design to air pollution by
378 calculating three capacities: the capacity of urban design to decrease emissions (fig. 8); its capacity to
379 decrease concentrations and its capacity to decrease exposure. This method has been applied to
380 Greater Paris.
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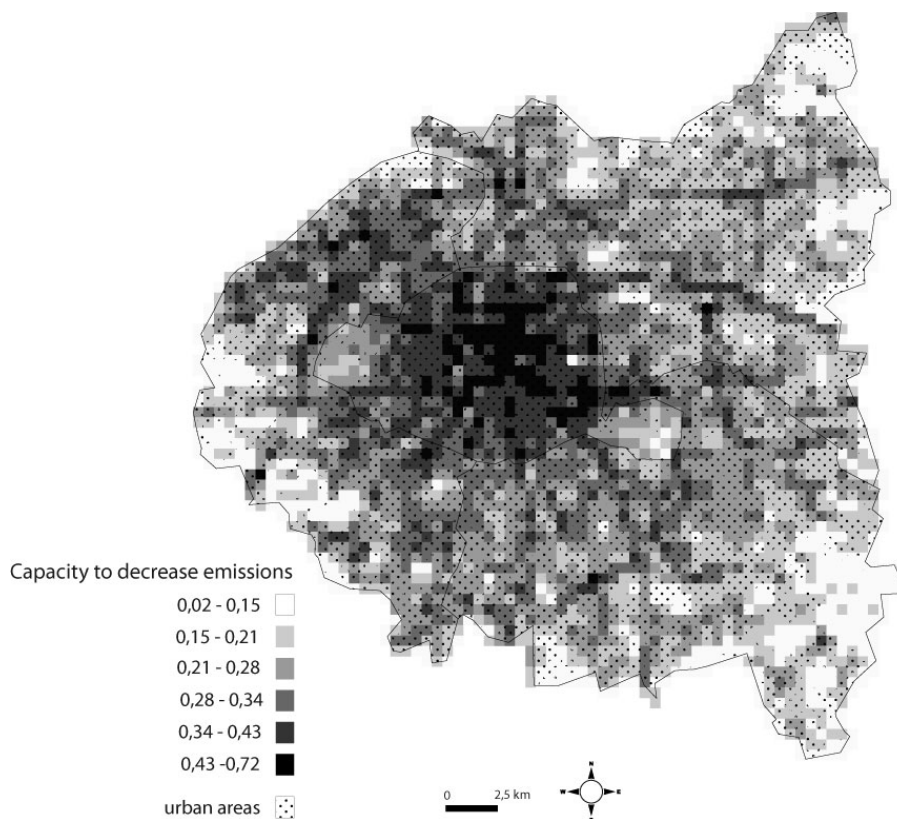


Fig. 8. Capacity of Greater Paris to decrease emissions (source: Cariolet *et al.*, 2018)

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Bertilsson *et al.* (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).

391

Recently, Martins *et al.* (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 active modes in case of a disruption of the mobility system.

395

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.

400

401 3. Discussion

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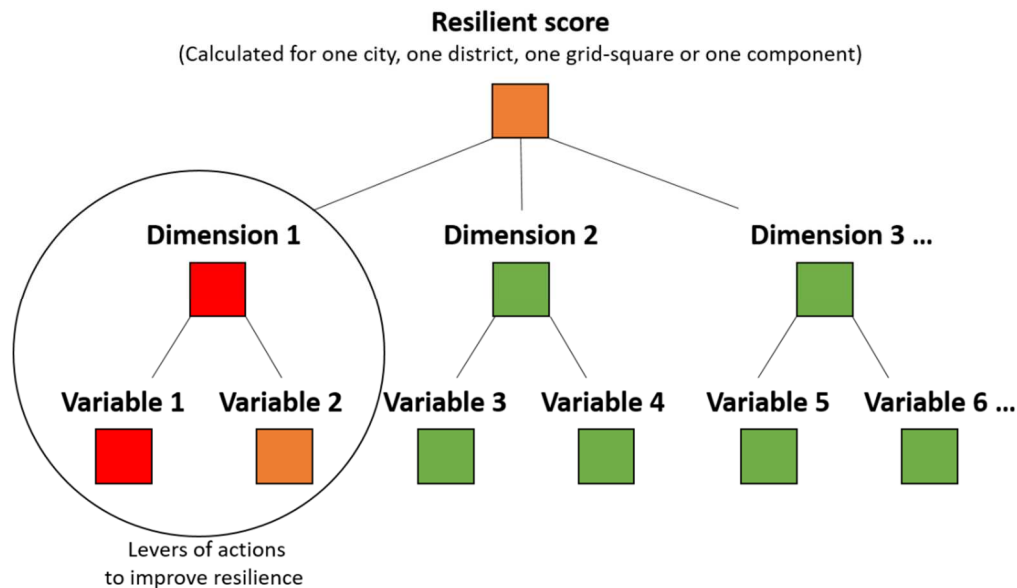
403 3.1. Mapping resilience: what contribution to disaster management?

404

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

411

412 to highlight the reasons for lower scores and devise appropriate actions together with the methods
 413 for developing these (fig. 9).
 414



415
 416 *Fig. 9. Deconstruction of the resilience score for one geographical object (a city, a district, a grid-*
 417 *square or a component). In this case, the resilience score is high when green, average when orange*
 418 *and low when red. The low scores of variables 1 and 2 explain the resilience score. In order to improve*
 419 *resilience for the geographic object, variables 1 and 2 need to be improved.*

420
 421 In general, we observe that resilience is presented as a new conceptual risk management framework
 422 leading to more effective consideration of the time variable and systemic effects (Ehret *et al.*, 2015).
 423 The relatively consensual nature of the indicators selected for the study of hazards (example: water
 424 levels or current velocity for a flood) greatly facilitates the mapping of its phenomena. We note that
 425 this is more complicated for vulnerability which can be defined as the propensity of a person, a
 426 building, a material infrastructure, but also an activity, an economic sector or, more broadly, a
 427 society or a territory to be damaged (Laganier, 2016). Vulnerability is often mapped using a
 428 subjective analytical approach (Heesen *et al.*, 2014). In other words, vulnerability is assessed by
 429 adding up numerous variables chosen subjectively. This is also the case with inherent resilience
 430 which is why it appears complicated to map resilience and to understand such mapping (tab. 3). The
 431 “porosity” between vulnerability and resilience mapping – in the sense that resilience is sometimes
 432 expressed as the opposite of vulnerability - adds more confusion.

433
 434 *Tab. 3. Difference between hazard, vulnerability and resilience mapping*

Hazard mapping	Vulnerability mapping	Resilience mapping
<ul style="list-style-type: none"> ▪ Physical modelling or <i>in situ</i> measurements ▪ Few variables mapped 	<ul style="list-style-type: none"> ▪ Subjective analytical approach ▪ Infinity of variables can be mapped 	<p><i>Adaptive resilience:</i></p> <ul style="list-style-type: none"> ▪ Dynamic approach ▪ Few variables can be mapped (sectorial approach) <p><i>Inherent resilience:</i></p> <ul style="list-style-type: none"> ▪ Subjective analytical approach to measuring a dynamic capacity ▪ Infinity of variables can be mapped

435
 436 According to Heesen *et al.* (2014), several aspects of vulnerability and resilience cannot be easily
 437 mapped, such as “specific forms of knowledge and interpretation, the processuality of vulnerability

438 and resilience, the dynamics of social processes, the context of origin, the establishment of
439 contingent interpretations, and so on” (Heesen *et al.*, 2014, p74).

440

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

444

445 3.2.A missing systemic approach

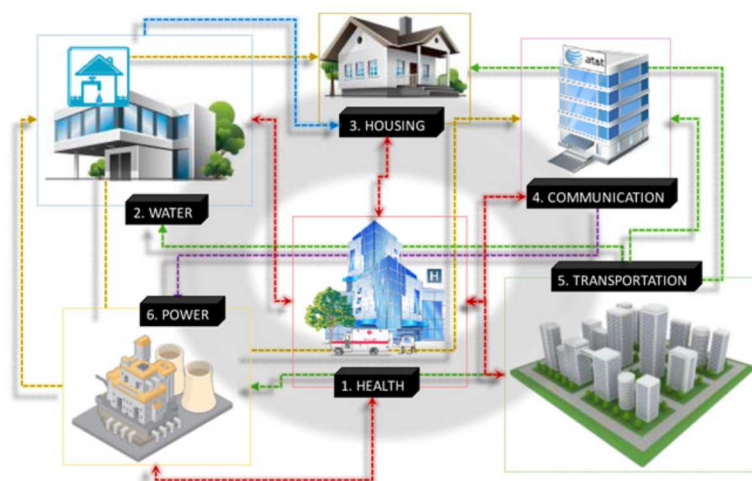
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447 Most of the methods for mapping inherent resilience identified in this review are analytical and do
448 not integrate the systemic property of resilience. According to Reghezza (2016), resilience is often
449 considered aspatial due its systemic property. There is no doubt that the systemic character of
450 resilience - generating a large number of possible connections and states, feedback loops as well as
451 multiple parameters that are difficult to predict, describe or even identify – singularly complicates
452 the production of general indicators and hence indisputable global maps. Nevertheless, the different
453 aspects of resilience can be broken down (e.g.: various resilience factors, action plan components for
454 a more effective relaunch of operations, planned functioning of urban systems in degraded mode,
455 etc.) into as many maps useful for implementing actions aimed at improving urban resilience. Along
456 with vulnerability-based analytical mapping elements, maps used for resilience studies potentially
457 provide richer decision support but are also harder to interpret as the user has to think about their
458 systemic implications.

459

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

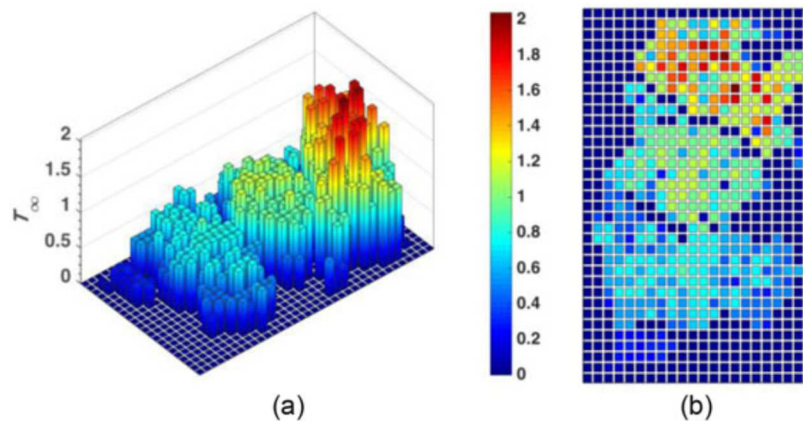
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468

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

471



472
 473 *Fig. 11. Time to stabilization (T_{∞}) values obtained for Housing lifeline in Gotham City (Source:*
 474 *Mahmoud and Chulahwat, 2018)*
 475

476 3.3. Scale, granularity and data availability

477
 478 Most of the methods developed to map community resilience have been applied at continental
 479 (Ross, 2014; Lam *et al.*, 2015), national (Cutter *et al.*, 2014; Siebeneck *et al.*, 2015; Suarez *et al.*, 2016;
 480 Kammouh *et al.*, 2018), or regional scale (Cutter *et al.*, 2010; Joerin *et al.*, 2014; Cai *et al.*, 2016;
 481 Kuscahyadi *et al.*, 2017) using spatial units such as countries (Sherrieb *et al.*, 2010), regions
 482 (Siebeneck *et al.*, 2015; Suarez *et al.*, 2016), counties (Cutter *et al.*, 2010 and 2014) or city
 483 administrative boundaries (Joerin *et al.*, 2014; Yoon *et al.*, 2016; Tyler *et al.* 2016 ; Kuscahyadi *et al.*,
 484 2017; Schlör *et al.*, 2018; Miles and Chang, 2011). As pointed out by Kontoskosta and Malik (2018),
 485 “most of these models either lack data at the spatial granularity needed to adequately represent
 486 urban neighborhoods – resulting in several studies that instead use counties or other large
 487 administrative divisions” (page 273). Recently, Cai *et al.* (2016) managed to use a fine spatial
 488 granularity at a regional scale using census blocks. However, only a few recent papers have mapped
 489 urban resilience specifically, i.e., on a city scale. Census **tracts** are the most common spatial unit used
 490 at this scale (Kontoskosta and Malik, 2018; Serre and Heinzlef, 2018) but they do not always provide a
 491 detailed understanding of the spatial distribution of resilience indicators in an urban area.
 492 Researchers appear forced to choose or dismiss certain indicators because of data availability.
 493 Furthermore, maps based on aggregation are affected by the Modifiable Areal Unit Problem (MAUP).
 494 The choice of spatial units and their scale may affect the results (here the score of the resilience
 495 index), which may lead to spurious inequality between units. This can be worsened when similar
 496 spatial units are grouped (Larsen, 2000). Such maps are thus dependant on the mapmaker’s choices,
 497 and we can wonder how sensitive the fuzzy concept of resilience is to these choices. MAUP
 498 sensitivity analysis should be performed systematically in order to validate such results.
 499

500 When data is available, it is possible to map the resilience capacity of the components of a system
 501 studied (Lhomme *et al.*, 2013; Cimellaro *et al.*, 2015; Chopra *et al.*, 2016; Aydin *et al.*, 2018; Zhang *et al.*,
 502 2018). In France, the national reference system of vulnerability to flooding (*référentiel national*
 503 *de vulnérabilité aux inondations*) maps recovery capacity (IAU, 2017). These maps are prepared by
 504 overlaying the hazard, the areas of electrical fragility and the components of the territories that
 505 participate in the recovery of a given territory (nurseries, hospitals, institutions schools, metro
 506 stations etc.). This type of mapping has the advantage of providing more information on resilience
 507 than maps which use surface elements only. Nevertheless, in dense territories, the maps are often
 508 overloaded with elements and not very legible.

509 Finally, other researchers use grid-based approaches in order to gather data with different
 510 granularities (Renschler *et al.*, 2010; Cariolet *et al.*, 2018). Grid-based approaches are particularly
 511 interesting when the smallest administrative spatial unit is too big for the territory studied.

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3.4. 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 *et al.*, 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).

3.5. 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 tab. 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 tab. 2 are revealing. Resilience is context-dependent and cannot be measured everywhere with the same variables and indicators. Furthermore, holistic standardized resilience 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.

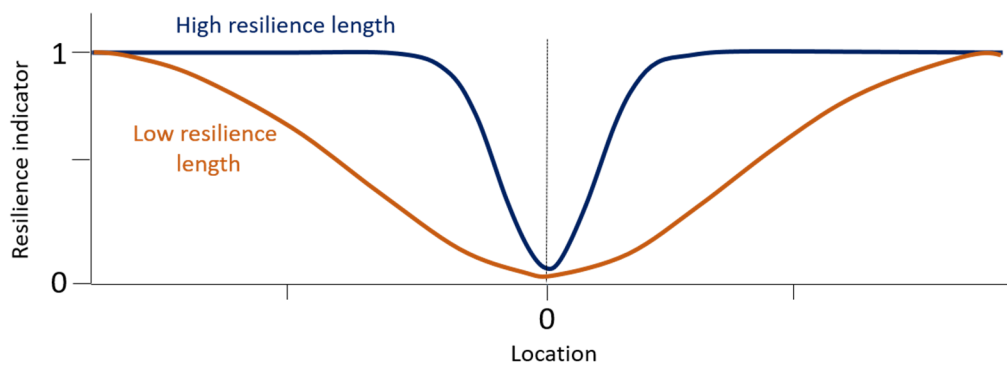
Web mapping should also help improve urban resilience to disasters in the future. According to Tate *et al.*, (2011), web mapping enables the development of applications that are dynamic, and accessible for everyone. Furthermore, it enables disaster managers to spend more time creating effective planning and strategies instead of collecting data and creating maps. Based on collective

564 and public participation, web mapping is perhaps a key mapping strategy for dealing with urban
565 resilience as it enables to access to large scale data. During recent disaster events (South-East Asian
566 tsunami in 2004, Hurricane Katrina in New Orleans in 2005, Haiti earthquake in 2010 etc.),
567 **Volunteered** Geographic Information (VGI) have been used and proved to be useful during disaster
568 management (Roche *et al.*, 2013). However, future researches need to be conducted to analyses
569 potential miss-use and associated risks regarding the use of web mapping for mapping or improving
570 resilience.

571
572 The review shows that it is currently not possible to map the resilience of a city entirely because the
573 level of complexity is too great. We suggest that researchers first need to focus on the resilience of
574 sub-systems and hazards instead of trying to be holistic.

575
576 Researchers working on urban resilience could once again be influenced by ecological resilience in
577 the future. Ecology proposes new concepts and ways of measuring and mapping the resilience of
578 ecosystems which could be applied to urban systems. Among them, the concept of **recovery** length is
579 promising as it deals directly with the spatial dimension of resilience. Dai *et al.* (2013) define the
580 concept of **recovery** length as the distance that a system must be from a localized disturbance for it
581 to recover its normal functioning. In resilient systems, the distance of disfunctioning is less than in
582 non-resilient systems (fig. 12). This concept could help in comparing the resilience of different
583 complex systems or even predicting their future transitions – or tipping points.

584



585
586 *Fig. 12. Recovery length is the distance that a system must be from a localized disturbance for it to*
587 *recover its normal functioning. In resilient systems, the distance of disfunctioning is lower than in*
588 *non-resilient systems (adapted from Dai et al., 2013)*

589

590 4. Conclusions

591

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

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

603 We suggest that research needs to be developed based around intermediate or hybrid methods (i.e.,
604 mixing top-down and bottom-up approaches) and focusing on the resilience of sub-systems as it is
605 still not possible to map urban resilience totally as the complexity is too great. Ways of integrating

606 systemic approaches into urban resilience mapping need to be developed too. Finally, as maps are
607 mainly meant to be used by decision makers, such methods should be co-created along with them.
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