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Urban resilience patterns after an external shock: An exploratory study

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ABSTRACT

Resilience has in recent years become an established concept in dynamic systems analysis. It is also increasingly employed in dynamic spatial systems, such as cities. The present paper offers an evidence of resilience of urban systems after an external shock. It pays particular attention to natural disasters affecting a city's system. A typology of different types of disasters and of related damage is presented, from a global perspective on the regional occurrence of such calamities. The cost and recovery potential after an external shock are statistically explored. We find that population size and density are critical parameters for the order of magnitude of disaster damage. The comprehensive approach to urban resilience based on risk assessment, identification and management proposed in this paper helps to depict a feasible urban resilience pattern after an external shock.

1. Introduction

Several years back, Brakman et al. [8] published a study on the long-term consequences of strategic bombing of German cities by the Allied Forces during WWII for the post-war city growth in (East and West) Germany. Such a shock in the growth trajectory of cities may have short-term negative effects, long-term negative effects or long-term positive effects. Their analysis is an example of the rising volume of empirical studies on urban resilience trajectories, which aim to analyse the dynamic recovery potential of cities after an external shock.

Cities – urban agglomerations and metropolitan regions – are complex and interrelated geographic entities that exhibit a wide variety of dynamic behaviours over time (see e.g. [30,32,56]). Despite the universal and world-wide urbanization mega-trend, not all cities on earth have an identical growth pace; some cities may show an unprecedented growth rate and turn even into megacities, while others may exhibit a stagnation or even a decline (see [19]). Urban growth and urban shrinkage are often taking place simultaneously, although rapid urbanization is a dominant trend nowadays. Urban areas are frequently showing a life-cycle pattern with upturns and downturns, which are sometimes similar to business life-cycles in industry. The amazing urban dynamics has led to a wealth of informed studies that document these evolutionary urban trajectories and transition points therein (see e.g. an early seminal study on the life course of cities by [7]). In the past decade, an avalanche of conceptual and applied studies on urban growth and decline under different economic, technological and political regimes has been published (see e.g. [12,13,20,26,28,29,40]). Haase [19] produced an interesting overview of several important trends in urban dynamics. In particular, issues related to urban robustness, vulnerability and resilience have been given much attention in the literature.

Urban economics may, in general, be subject to various types of fluctuations, ranging from cyclical movements to external shocks. The latter type of dynamics may find its origin in both global or national-regional forces and determinants. Such shocks may include inter alia layoffs, economic recession, unexpected migration influx, ageing population and catastrophes of various kind. The urban ability to absorb such shocks is usually referred as resilience [10,35,48]. This concept has gained much popularity in recent years, including its measurement, which may use a single or composite parameter index.

Noteworthy contributions to an appropriate understanding of resilience mechanisms and vulnerability analysis can be found inter alia in [2,6,33,50,51], low predictability and nonlinear development are typical features of vulnerable systems. Urban evolution – often mapped out in the form of nonlinear growth trajectories – is the result of a complex internal, external and policy force field.

It is remarkable that cities vary enormously in their adaptive capacity to new or unexpected challenges, due to several crucial factors such as governance, institutions, cultural habits, technology, wealth, urban planning, and their ability to respond to such challenges.

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Resilience increases when cities have more adaptive capacity, and decreases when they are more vulnerable. Exponential population and economic growth is nowadays placing so much pressure on resources that resilience, which has for long been an almost free gift of history, urgently needs to be re-thought or re-activated [5]. In contrast to a regular life-cycle pattern of urban agglomerations caused by endogenous forces of a city or urban system (as studied in the earlier urban system dynamics literature; see [17]), this study addresses unforeseen external shocks that impact the urban economy and that lead to disequilibrating forces in cities, without any prior guarantee of a stable outcome or a return to the initial position, and the factors or variables driving its behaviour. Thus, the present paper aims to identify and analyse a set of relevant indicators of an urban system (e.g. population size, density of population, economic prosperity as measured by the GDP per capita and degree of urbanization) impacting on the occurrence, quantity of persons affected, and economic damage caused by selected types of natural disasters and to outline possible urban resilience patterns after an external shock.

The present study is organized as follows: Section 2 conceptualizes several notions associated with resilience and vulnerability of cities, as well as the drivers and building blocks of resilient cities, while their relationships are also explained in this section. The next section (Section 3) details the database and the methodology used in the present paper; data mining and data sources are described as well. Section 4 aims at presenting our empirical research results. Based on the results from the two previous sections, a subsequent section (Section 5) discusses possible urban resilience trajectories after an external shock. Finally, Section 6 concludes with a discussion of policy lessons learnt and suggests future steps for research.

2. Resilience and vulnerability of cities

Cities are dynamic organisms that are subject to the laws of life and death. The capability of cities to thrive as centres of human habitation, production and cultural development is – despite the challenges posed by negative externalities, climate change, various types of disasters, population growth and globalisation – positively co-determined by their resilience potential [5].

Resilience has already a long tradition in biological and engineering sciences, but only in the last decade this concept has gained much popularity in the urban and regional sciences (see e.g. [35,37,48,52,54,55]). The concept refers to a dynamic system which – after an external shock – may have a compensating or equilibrating mechanism to bring it back to its initial position (‘bouncing back’). In the literature, sometimes a distinction is made between engineering and ecological resilience, depending on whether a transition to the original or a new equilibrium emerges [49]. This refers to so-called ‘functional’ resilience. In contrast to functional resilience, ‘dynamic’ resilience describes the tendency of a system to resist a collapse and to maintain structure and function. The dynamic interpretation of resilience more appropriately represents the complexities and chaos evident across the world. This concise review shows the multiple and sometimes conflicting ways in which resilience is interpreted. This diversity which prompts also criticism is also seen as a strength by others, by bringing together otherwise disjoint groups, institutions, disciplines and scales and leading to different operational approaches [67]. Various resilience indices has been developed in the recent literature, but thus far no unambiguous and universally accepted resilience measure has been found, mainly because the system's boundaries and the transition time needed may vary substantially.

Resilience – as both a scientific and a policy concept which refers to the recovery potential of dynamic systems – has in recent years boosted a great interest. Resilience refers in general to the ability of actors to develop and implement adaptation strategies and operational mechanisms to external perturbations that mitigate the long-run effects of such shocks and that may lead to a restoration of the initial equilibrium or to the realization of a new equilibrium state. Resilience may thus be considered as “the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks” ([57], p. 8).

In the literature, resilience refers to four main abilities: (1) the ability to absorb economic, environmental or social shocks or stresses, to accommodate and to mitigate the impact of these shocks, while retaining the capacity to carry out essential functions and without passing it on to other entities [41]; (2) the ability to adapt to change, to adapt its structure to adjust, modify or change under changing circumstances [35,47]; (3) the ability to transform outcomes in a face of a challenge [11] in terms of creation a fundamentally new system, so that the shock will no longer have any impact; (4) the ability to be prepared to learn from past shocks and stresses, and plan in advance to anticipate the future shocks to perform better than before [41].

Based on the above mentioned abilities, resilient urban systems might be characterized as systems able to absorb, adapt, transform and prepare for the past and future impact of economic, environmental and social shocks or stresses, in order to promote sustainable development, well-being and to maintain an acceptable growth pattern [11,35,41,47]. Urban resilience is consequently understood as “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” ([66] p. 39).

Similar to resilience in general, urban resilience is also a contested concept that still lacks clarity due to some ambiguity, inconsistencies, challenges associated with defining and characterizing “urban” and “resilience” individually, and numerous disciplines engaged in this field of study. It leads to a multitude of different definitions and conceptual tensions [64,66]. In this context, Meerow et al. ([66] pp. 40–43) have summarized and reviewed the scope and challenge of urban resilience definitions. According to their research, half of the definitions are presented in the context of a specific threat (e.g., climate change or flooding), while the other half focuses on the resilience of an urban system to respond to risks. They also define six conceptual tensions in definitions of urban resilience, namely: characterization of urban, notion of equilibrium, resilience as a positive concept, pathway to resilience, understanding of adaptation, and time-scale of action. The majority of definitions fail to take a clear position on at least one of these six conceptual tensions. Definitions uniformly portray urban resilience as a desirable goal, more than half of them adopt non- or multi-equilibrium resilience. More than half emphasizes high levels of general adaptive capacity as opposed to adaptedness. Only a few definitions include a mechanism for changing from an undesirable state, and even fewer mention a time-scale for action, in a post-disturbance period (for more information, see [66]).

The occurrence of urban resilience after an external shock is influenced by a multiplicity of factors, including geographic location, the initial and prevailing social and economic situation, the level and quality of infrastructure, density of population, social capital, cultural habits, environmental conditions, institutional frameworks, and many other things. Although there may be different levels of suffering from – or different impacts of – natural disasters or external perturbations in different countries or regions all over the world, it is clear that the issue of shock recovery is a global concern. This holds no doubt also for cities in our world.

The theoretical framework of urban resilience, firstly introduced by the Resilience Alliance in 2007 (see first picture in Fig. 1), pointed out a number of unanswered questions and needs of its implementation. Multi-level understanding of resilience of urban systems recognizes the role of metabolic flows in sustaining urban functions, human well-being and quality of life; governance networks and the ability of society to learn, adapt and recognize to meet urban challenges; the social dynamics of people as citizens, members of communities, users of services,

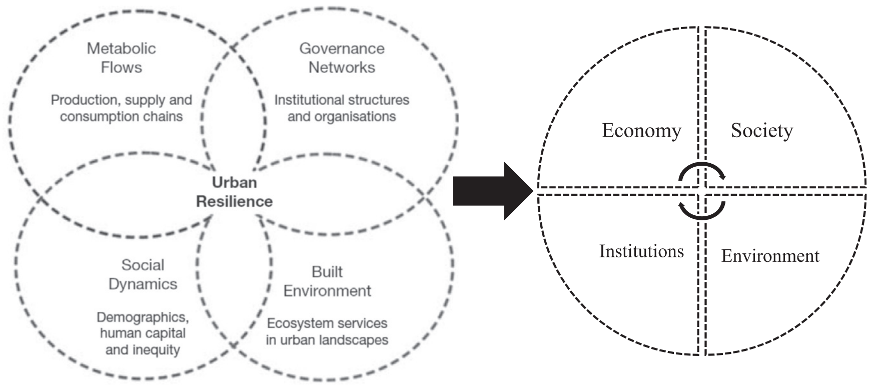


Fig. 1. Multi-level understanding of resilience of urban systems and drivers of resilience.
Adapted from [42,62].

consumers of products etc. and their relationship with the built environment which defines the physical patterns of urban form and their spatial relations and interconnections [62]. Such a multi-level understanding of resilient urban systems leads us to important questions on how all the different fields in one framework will deal with one coherent urban resilience perspective analysis of cities, how urban resilience is related to planning in practice or governance, and how it can use insights and links with governance, economy or climate change adaptation [62,63].

A recent study by the OECD Ministerial Council identified four main drivers and several sub-drivers and facilitators of resilience [42]. These four main drivers are coherent with a multi-level understanding of resilient urban systems, as shown in Fig. 1.

The first driver of resilience in Fig. 1 is *economy*. Resilient cities have diversified industries, including those based on knowledge and empowered by creativity, and are thus able to generate a great potential for innovation. The level of diversification of economic activity, and the effectiveness of their specialisation in building competitiveness, will influence the internal economic drivers [22,35]. This is also relevant for an overall exposure in global economic value chains. Reliable infrastructure and skills, knowledge, creativity and experience of the labour force contribute to enhancing resilience [15,41].

A second driver of resilience is *society*, with cohesion and inclusion as prominent attributes. Resilient cities are able to cope with shocks by adopting a co-ordinated and coherent set of economic and social policies and practices. In particular, inclusiveness, right balance between communities and their interactions, and citizens' access to jobs and education can help cities to smoothly address and implement considerable changes (see inter alia [35,36,58,59]). According to Leykin et al. [34] preparedness, leadership and collective efficacy enables community to cope effectively with various challenges posed by an emergency or disaster. Therefore, "policymakers, emergency management agencies, researchers and the public will need to work together as a community of practice in many aspects of operationalizing ideas of disaster resilience" ([44] p.9).

Next, the third driver of resilience is the *environment*, focusing in particular on sustainability. Climate change adaptation and planning are shaping or supporting resilience [53]. Resilience matters in the face of environmental degradation, the over-use of resources and the potential costs of climate change and natural disasters. Environmental factors are critical for cities because of the large number of people living in relatively densely populated areas and the complexity of the systems that interact with them, including infrastructure networks, communication systems, transport, water and energy distribution, housing and urban green spaces [16,23,38,47]. The current world – with its recent population growth and industrialisation trend – may, despite many global benefits, destabilise environmental systems and make previously safe places more vulnerable than they were ever before [5]. "Understanding the complexity of vulnerability to disasters, is at the heart of disaster risk reduction" ([36] p. 103). *Vulnerability* is related here to the robustness of a man-made system to cope with the emergence of external shocks and to combat its negative consequences; it is a shock absorption ability that reflects to some extent a risk-persistence of a system in a timely and effective manner. Reduction of vulnerability through deliberate actions may increase the resilience of the system concerned. Complex urban systems are particularly vulnerable to different types of natural disasters. Built-up environments are at greater risk of damages caused by natural disasters or a combination of interconnected natural disasters (for example, localised flooding after a heavy storm may lead to contamination of water for household consumption). Building environmental resilience also needs preparedness at local level to understand how climate change will influence local communities and to take action to safeguard human well-being community assets [24,36,60].

A final driver of resilience is formed by *institutions*, based on the social capital principle of openness and collaboration. Resilient cities ensure open, transparent and inclusive policymaking and enable effective policy implementation. Institutions play a key role in strengthening resilience, since the impact of any shock depends on the institutional capacity to respond and rebound from shocks. Adaptive capacity of local policy actors is crucial in terms of reflection on desired futures [42,45]. In particular, city authorities are on the front line of efficient governance by delivering public services, and building trust in governance. Capacity building in local governments and development in human resources are indispensable for resilient institutions, because the capacity to reform institutions determines regional resilience [3,43].

According to [4,16,25,27,41] it is possible to identify systematically critical building blocks for resilient cities (see Table 1).

The drivers of resilience (see Fig. 1) are in turn influenced by endogenous factors, such as the culture, society, politics, economy, environment and demography of a given city. Their strength varies depending on a series of qualities intrinsic to resilient systems. These include the capacity to become adaptive, robust, redundant, flexible, resourceful, inclusive and integrated, as will be explained below. We understand these drivers as the basic pillars of resilience that are arising – like a house built on solid foundations – from the adaptive, robust, flexible, resourceful, inclusive, redundant and integrated building bricks (see Fig. 2). This architecture will be explained underneath.

There is an important agreement on perception resilience as a desirable attribute [66] that contributes to sustainability [65] and ability, not only to maintain but also to improve and prosper [61]. In our point of view, resilience of cities can be perceived as a "roof" or "umbrella" of an urban system, enhanced by economy, society, institutions and environment and supported by the foundations stones: adaptability, robustness, flexibility, resources, inclusiveness, redundancy and

Table 1
Relations between drivers of resilience and building blocks for resilient cities.
Source: OECD, 2016, pp.31–32

		Building blocks						
Drivers	Sub-drivers	Adaptive	Robust	Redundant	Flexible	Resourceful	Inclusive	Integrated
Economy	Industries are diverse and generate growth							
	Innovation takes place and leads the economy							
	The workforce has diverse skills							
	Infrastructure supports economic activities							
Society	Society is inclusive and cohesive							
	Citizen networks in communities are active							
	People have access to public services							
Environment	Urban development is sustainable							
	Adequate and reliable infrastructure is available.							
	Adequate natural resources are available							
Institutions	Leadership and long-term vision are clear							
	The public sector has proper resources							
	Collaboration with other governments takes place							
	Government is open and citizens' participation takes place							

Note: This table shows where the linkages are the most obvious and relevant. Darker cells indicate more obvious and relevant linkages than lighter-coloured cells, although this does not necessarily mean that they have no linkage with building blocks and drivers.

integration. An *adaptive* urban system has a strong human and policy interface: it manages uncertainty on the future by evolving – modifying standards, norms or past behaviour – using evidence to identify solutions and applying the knowledge gained from past experience in taking decisions about the future. "Adaptive capacity is a critical determinant of overall system resilience, and the adaptive capacity of individuals, communities and regions affects the "resilience landscape" of any city" ([63] p. 11).

A *robust* urban system is characterized by stability and ability to absorb shocks and to survive without a significant loss to its functionality or capacity to function. *Redundant* urban systems are able to meet the need for spare capacity when faced with unexpected demand, a disruptive event or extreme pressure. A *flexible* urban system allows individuals, households, businesses, communities and government to adjust behaviour or action in order to effectively respond to change in a moment. A *resourceful* urban system can effectively and quickly restore the functionality of its essential services and systems in a crisis condition, or under highly constrained conditions, meeting its needs, maintaining its purpose and achieving its aims in times of shock or stress, with the limited resources available. An *inclusive* urban system

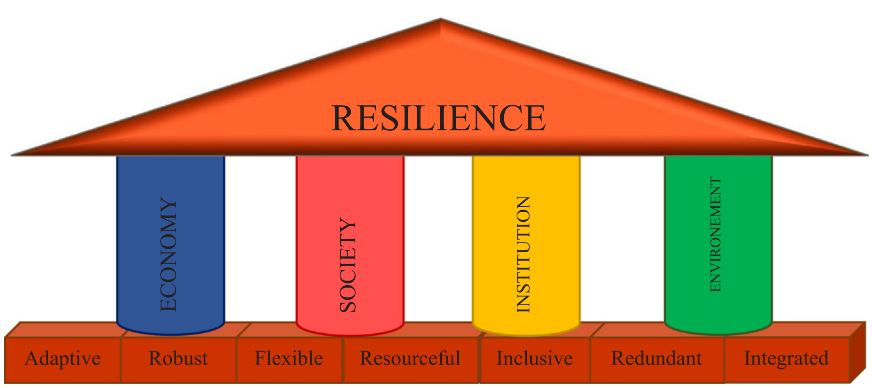


Fig. 2. "Umbrella" concept of resilience interlinking main drivers and building blocks.
Own processing based on [16,33,35,37,41,45,51,53,57]

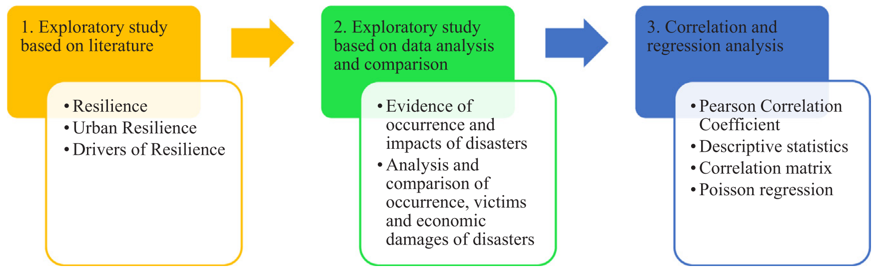


Fig. 3. Realization of qualitative and quantitative research.

ensures that diverse actors and communities are fully consulted, engaged and empowered in the policy process (e.g. through policy programming and local initiatives), by including them in the policy design stage whenever possible. An *integrated* urban system promotes a cooperative and, ideally, collaborative or participatory approach beyond sector boundaries (public and private as well as policy sectors) and administrative boundaries to policy and programming, to better ensure coherent decisions and effective investments. (for more details see [16,33,35,37,41,45,51,53,57]). With all building blocks linked to the drivers, the various linkages and constitutes of resilience in cites are summarized in Table 1 [41].

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 or original functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity ([66] p. 45). Urban resilient systems are conceptualized as adaptive, robust, redundant, flexible, resourceful, inclusive and integrated ecosystems composed of four drivers - economy, environment, institutions and society - that are strongly coupled and networked.

In the light of plausible evidence from our literature search we have focused in this section on exploratory study of resilience. We reviewed different approaches to resilience starting from engineering and ecological resilience and the shifting to functional and dynamic resilience. We introduced resilience as a scientific, but also as a policy concept. Similar to general, also urban resilience is a contested concept that still lacks clarity. In this section, we systematically introduced this intriguing concept and its multi-level understanding. Based on a rigorous literature review, we proposed an "umbrella" concept of resilience interlinking main drivers and building blocks of an urban system. In the next, third section we will address operational aspects of urban resilience analysis.

3. Data and methodology

This paper focuses on the recovery potential of cities after an external disruption. In order to cover this broad topic, both qualitative and quantitative research in several stages is undertaken. In the first stage, we focus on an exploratory study of resilience based on the literature (Section 2). In the second stage, an exploratory study of resilience based on data analysis is employed (Section 4). We offer evidence of occurrence of disasters and their economic impacts from 1980 until 2015. Subsequently, we focus on an analysis and comparison of occurrence, victims and economic damages of four selected natural disasters in 2015, measured in percentage shares. In the third stage, we perform a correlation analysis between degree of urbanization, population size, density of population, and population growth rate, and occurrence and impact of selected natural disasters across continents (Section 4). To enrich our statistical analysis, we also used descriptive statistics, a correlation analysis and a Poisson regression. The following figure (Fig. 3) shows the methodology employed.

A broad comparative and exploratory study of these phenomena would need a wide array of consistent information. There is indeed an avalanche of information on urban catastrophes and disruptions, but most of this information is available in anecdotal form e.g., in news (media or public debates). There is not much systematics in the definition and collection of urban disaster data, leave aside in the form of quantitative data.

There is only one exception: data inspection and mining for this particular paper has world-wide been undertaken through the Emergency Events Database (EM-DAT),[1] various reports from the Centre for Research on the Epidemiology of Disasters (CRED), United Nations data sets, and several OECD reports. EM-DAT uses a classification that was initiated by CRED with the aim to create – and agree on – a common hierarchy and terminology for all global and regional databases on natural disasters and to establish a common and agreed-upon definition of sub-events that is simple, accessible and self-explanatory. The data are compiled from various sources, including UN agencies, non-governmental organizations, insurance companies, research institutes and press agencies. In this context, CRED defines a disaster as "a situation or event that overwhelms local capacity, necessitating a request at the national or international level for external assistance; an unforeseen and often sudden event that causes great damage, destruction and human suffering" ([18] p. 7). For a disaster to be entered into the database, at least one of the following criteria should be fulfilled:

- 10 or more people reported killed;
- 100 or more people reported affected;
- declaration of a state of emergency;
- call for international assistance.

CRED distinguishes two generic categories for disasters, including natural disasters and technological catastrophes. In our paper we will focus only on natural disasters, which are subdivided into four main categories: geophysical disasters (earthquakes and tsunamis, volcanic eruptions, dry mass movements); climatological disasters (droughts with associated food insecurities, extreme temperatures and wildfires); hydrological disasters (floods including waves and surges, wet mass movements); and meteorological disasters (storms divided into 9 subcategories). Biological disasters (insect infestations, epidemics and animal attacks) are excluded from our study.

The methodology used in the present paper is as robust as possible, by exploiting several scientific and statistical methods with the aim to fulfil the scientific goal of studying resilience.

The main goal of the paper was – as mentioned before – aims to identify and analyse various appropriate indicators of an urban system

[1] Since 1988, the Centre for Research on the Epidemiology of Disasters (CRED), located in the School of Public Health at the Université Catholique de Louvain, has been developing and maintaining an Emergency Events Database EM-DAT. EM-DAT was created with the initial support of the WHO and the Belgian Government. The main objective of the database is to serve the purposes of humanitarian action at national and international levels. It is an initiative aimed at rationalising decision making for disaster preparedness and prevention, as well as at providing an objective base for vulnerability assessment and priority setting. EM-DAT contains essential core data on the occurrence and effects of over 20,000 mass disasters (13,800 natural and 8200 technological disasters across the globe) in the world from the year 1900 to the present.

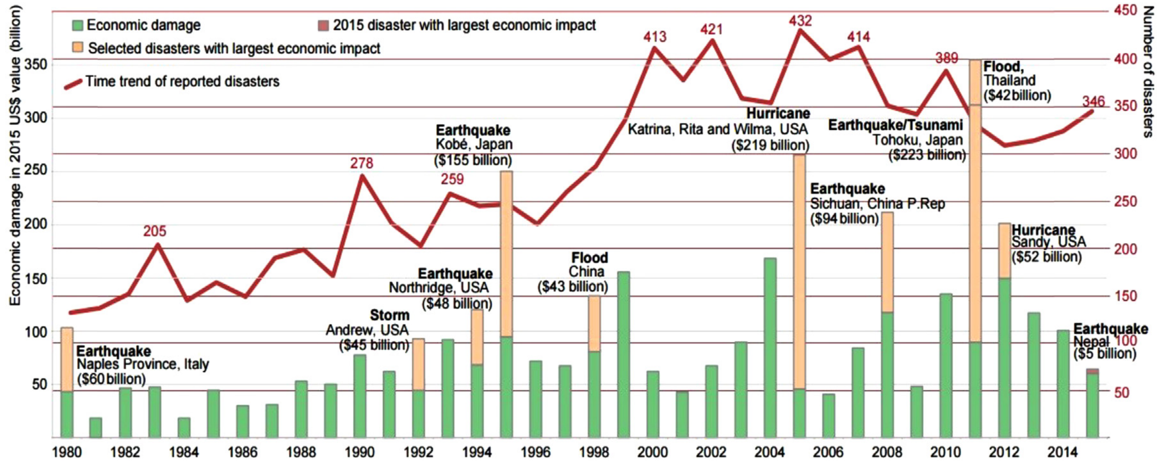


Fig. 4. Evidence of occurrence of disasters and their economic impacts from 1980 until 2015.
Centre for Research on the Epidemiology of Disasters, US Agency for International Development

(e.g. population size, density of population, economic prosperity as measured by the GDP per capita and degree of urbanization) impacting on the occurrence, quantity of persons affected, and economic damage caused by various types of natural disasters and to explore feasible urban resilience patterns after an external shock to the city. Under an external shock, we understand in this particular paper, one of the four selected types of natural disasters (climatological, geophysical, hydrological and meteorological).

The exploratory scientific research on urban resilience in this paper is based on a consistent literature review, statistical analysis, comparison, and evaluation of comprehensive data sets. As a tool for statistical analysis we used a standard correlation analysis between two relevant impulse-response variables and Poisson regression. We employed here the Pearson correlation coefficient, which is a test statistic that measures the statistical relationship, or quantitative association, between two normally distributed variables. Pearson´s r is calculated by the following formula:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{1}$$

where: n is the number of samples, x_i and y_i are the single samples indexed with i, $\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$ (the sample mean, and analogously for y).

The Pearson correlation coefficient is usually regarded as the appropriate method of measuring the linear association between two sets of variables of interest, because it is based on the method of covariance. It provides information about the magnitude of the association, or correlation, as well as the possible direction of the relationship (for more information, see [21]). To enrich this simple and statistical analysis, we also employ descriptive statistics and a Poisson regression. The Poisson regression is typically used to quantify the effect on (non-negative) count data like the number of events occurring during explicit time interval of a vector of independent variables. The distribution is based on the assumption that events and their impact are independently generated through a probability density function like:

$$P(y = y_i) = \frac{e^{-\mu_i}\mu_i^{y_i}}{y_i!} \tag{2}$$

In our main regression specifications, we study how the number of catastrophic events per year and their intensity (person affected and economic damage) change in response to economic activity, urbanization, and population agglomerations over time. Thus, for each year i, the probability of yi events occurring is given by Eq. (2). We further assume that the occurrence of such events is related to k independent variables x1, x2, …, xk, interacting to determine the expected number of events E(yi) = μ, where x1 is a vector of ones (Eq. (3)). For any values of x1, x2, …, xk, we can use the model to predict the risk μ of a rare event occurring in a specified unit of time i as follows:

$$\mu_i = \exp(x_{i1}\beta_1 + x_{i2}\beta_2 + \cdots + x_{ik}\beta_k) \tag{3}$$

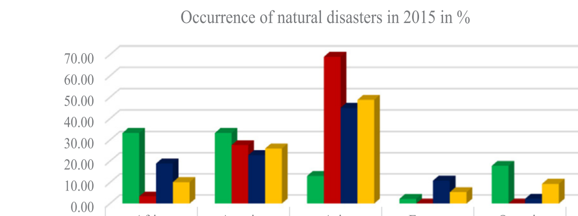
where β1, β 2, …, β k are the regression coefficients. Thus, Eq. (3) is the main regression equation to be estimated with the dataset available.

The dataset used in this study consists of a time series of world-wide natural disasters recorded between 1900 and 2015, although for practical purposes only data from 1960 are utilized due to missing observations, which gives us a total of 56 years for each of the 7 variables and a total of 392 observations. Data consist of nine columns categorized by the number of occurrences around the world, persons affected as well as the amounts of economic damage (Ecdamage, in thousand dollars). We transformed economic damage by dividing total damage by the number of people affected to create a variable of disaster intensity in per person-affected terms (dmgcap). With this specification, we acknowledge that disaster statements are based not only on the severity of an event, but also on the number of people affected. We also added information regarding density and urbanization in two variables: population in urban agglomerations of more than 1 million (agglomerations, % of total population) and urban population (urb, % of total) respectively, using information from the World Development Indicators database. In addition, we captured the effect of economic activity with GDP per capita (current dollars). Finally, we included a linearly-increasing variable corresponding to values from 0 to 55 to capture the upward time trend in our data. This explicitly recognizes that all covariates in the model are growing over time, as shown next in the correlation matrix (See Table 4 in the following section).

Clearly, we recognize that further research is needed, but for the time being this is the only database that is consistently available at a world-wide scale.

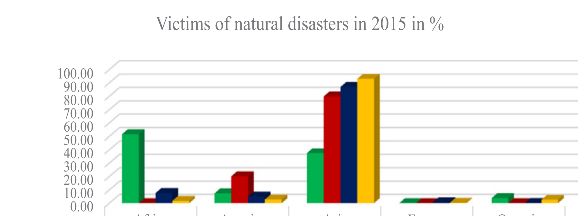
4. Research results

Disasters have a critical impact, not only on a city's environment, including its physical urban development, land use and topology, but also on its economy and society. In view of the high economic costs incurred by recent disasters, as well as the foreseen significant exposure to risk in the future, strengthening financial resilience to disasters has become a policy priority in many economies and cities, in both emerging and less developed nations as well as in developed economies [42]. Fig. 3 shows the economic damage of disasters from 1980 until 2015, the selected disasters with the highest economic impact, and the time trend of reported disasters.



	Africa	America	Asia	Europe	Oceania
Climatological	33.30	33.30	13.10	2.20	17.80
Geophysical	3.40	27.60	69.00	0.00	0.00
Hydrological	18.90	22.90	45.10	10.90	2.30
Meteorological	10.20	26.00	48.80	5.50	9.40

Fig. 5. Occurrence of four selected natural disasters in 2015 in percentage share.
Annual Disaster Statistical Review 2015



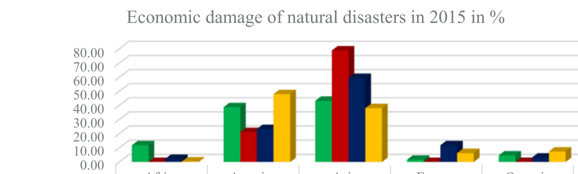
	Africa	America	Asia	Europe	Oceania
Climatological	51.50	7.30	37.40	0.00	3.80
Geophysical	0.00	20.10	79.80	0.00	0.00
Hydrological	7.60	4.90	86.90	0.60	0.10
Meteorological	1.70	2.70	92.90	0.20	2.50

Fig. 6. Victims of four selected natural disasters in 2015 in percentage share.
Annual Disaster Statistical Review 2015

Despite some discontinuities in the patterns in Fig. 4, we are witnessing a gradual rise in the occurrence of natural disasters. Due to rapid urbanization, urban disasters appear to have increasingly more serious economic impacts. As shown in Fig. 4, the most devastating economic impacts are caused by earthquakes, not seldomly connected with tsunamis in coastal areas, floods and hurricanes. As seen from the figure, the most devastating natural disasters were most often reported in the United States. A storm in 1992, an earthquake in 1994, a hurricane in 2005 and then again another one in 2012 caused economic damages of more than 364 billions of dollars. Japan had to cope with devastating earthquakes in 1995 and 2011 (in 2011 accompanied by a tsunami), with overall economic damages of 378 billions of dollars. China reported massive floods in 1998 and an earthquake in 2008, with overall economic damages amounting 137 billions of dollars. It is noteworthy that natural disasters with the highest economic impacts were reported from Asia and North America. Fig. 5 shows the percentage share of continents in world occurrence, victims and economic damages of selected types of natural disasters in 2015.

Fig. 5 shows that Asia is the most unsafe continent and Europe is the safest continent from the perspective of the occurrence of natural disasters. If corrected for population size and/or for a surface of continent, the figures will of course be rather different. It should be added that Asia has also a large volume of big cities, so that the impact of disasters may be very substantial. The costs may thus also vary substantially per continent.

Fig. 6 offers a description of the number of victims caused by natural disasters in various continents. It turns out that the death toll is very high in Asia, for almost all kinds of natural disasters. This pattern is consistent with that in Fig. 5. For the remaining continents, the number of victims is relatively lower, except for climatological disasters in Africa. One comment has to be mentioned here: the number of victims is recorded in numbers per continent, and not standardized for the total population size in a given continent. Seen from that perspective, the figures from Asia (and also Africa) are far less unfavourable. Unfortunately, there are no systematic reliable figures on urban disasters in these continents.



	Africa	America	Asia	Europe	Oceania
Climatological	11.80	38.70	43.20	1.60	4.70
Geophysical	0.00	21.10	78.90	0.00	0.00
Hydrological	2.20	23.30	59.50	11.80	3.20
Meteorological	0.40	47.90	38.00	6.30	7.40

Fig. 7. Economic damage of four selected natural disasters in 2015 in percentage share.
Annual Disaster Statistical Review 2015

The economic damage of natural disasters (Fig. 7) shows an interesting pattern compared to Figs. 5 and 6. The damage figures for Asia correspond to the frequency and number of victims from natural disasters. However, the economic damage in America appears to relatively very high, which may be caused by the high costs of expensive infrastructure and costly built environment in this continent. Also a destruction of urban areas in this continent may be very expensive.

Table 2 shows the Pearson Correlation Coefficient, respectively, for: degree of urbanization[2] (percentage of urban population pre continent in total population), population size (in % of the world population), density of population, and population growth rate (in %) in relation to occurrence, victims and economic damages caused by different kinds of natural disasters, respectively. All data used refers to the year 2015 per continent.

Table 2 shows several interesting patterns. On the horizontal axis (degree of urbanization, population size etc.), it turns out that there is in almost all cases a negative correlation between degree of urbanization and climatological, geophysical, hydrological and meteorological disasters (in terms of occurrence, victims and economic damage). For population size however, the pattern is just the opposite: in almost all cases there is a positive correlation. The same holds for density of population. Finally, the correlation between population growth rate and the four classes of damage are largely negative.

The following table (Table 3) shows descriptive statistics of worldwide catastrophic events.

The average year in our data had 371 declared disasters (and a median of 390) that affected 130,000 persons (101,000) at a total cost of US$51 billion (US$27 billion), or US$580 (US$270) per affected person.

In Table 4 we compute a correlation matrix for the dataset. Each disaster declaration is associated with an increase in agglomeration, urbanization, and GDP per capita at the world-scale level. The number of affected people and the associated economic damage are also positively affected by the same variables, but with a substantially smaller effect than in the case of disaster occurrences.

Parameter values are estimated using the maximum likelihood method. In Tables 5–7 we report our main results. To interpret these results we take the exponential of each estimated coefficient (column 6) and then we calculate 1-exp(coefficient) as in column 7.

Thus, in Table 5, the dependent variable is the number of occurrences, while the covariates are per capita economic damage, agglomerations, urbanization, GDP per capita and time trend. Columns 6 and 7

[2] Degree of urbanization refers to the proportion of people living in localities or urban settlements among the population of a municipality or a rural area whose place of residence can be defined by coordinates. According to ([68] p. 4) "there is no common global definition of what constitutes an urban settlement. As a result, the urban definition employed by national statistical offices varies widely across countries, and in some cases has changed over time within a country. The criteria for classifying an area as urban may be based on one or a combination of characteristics, such as: a minimum population threshold; population density; proportion employed in non-agricultural sectors; the presence of infrastructure such as paved roads, electricity, piped water or sewers; and the presence of education or health services".

Table 2
Correlation between degree of urbanization, population size, density of population, and population growth rate, and occurrence and impact of selected natural disasters across continents.

		Climatological	Geophysical	Hydrological	Meteorological
Degree of urbanization	Occurrence	− 0,18	− 0,29	− 0,47	− 0,28
	Victims	− 0,95	− 0,34	− 0,52	− 0,48
	Econ. damage	− 0,11	− 0,33	− 0,22	0,28
Population size	Occurrence	− 0,16	0,93	0,96	0,91
	Victims	0,55	0,96	0,98	0,97
	Econ. damage	0,73	0,95	0,93	0,43
Density of population	Occurrence	− 0,24	0,90	0,93	0,86
	Victims	0,54	0,94	0,98	0,97
	Econ. damage	0,66	0,93	0,91	0,43
Population growth rate in % (´10-´15)	Occurrence	0,71	− 0,16	− 0,03	− 0,11
	Victims	0,73	− 0,17	− 0,06	− 0,11
	Econ. damage	− 0,06	− 0,17	− 0,32	− 0,34

Table 3
Descriptive statistics of world-wide catastrophic events 1960–2015.

	Occurrences	Affected	Economic damage (US$ 000)	Economic damage (US$ 000 per affected person)
Min	33	143,713	529,905	0.02
Mean	371	129,149,062	50,545,970	0.58
Median	390	101,257,960	27,502,828	0.27
Max	896	659,332,560	364,095,869	10.6

suggest that an increase of 1% in agglomeration reduces the probability of occurrence by 99%. Similarly, an increase of 1% in urbanization reduces the chances of occurrences by 99%, compared to non-agglomerated and non-urbanized zones. The impact of per capita GDP on the probability of occurrences is more limited, namely around 0.02%.

In a similar way, Table 6 reports our main estimates for the effects on affected population. Experiencing a disaster is disruptive and for each declared disaster an increase of 1% in agglomerations and urbanization may reduce the expected impact on affected population by a magnitude of 99%. GDP per capita has a negligible impact on affected population.

Table 4
Correlation matrix of main variables in the database.

	Occur.	Affected	Ecdamage	Agglom.	Urban	GDPcap	Trend	Dmgcap
Occur.	1	0.67	0.64	0.88	0.89	0.83	0.90	− 0.07
Affected	0.67	1	0.41	0.51	0.53	0.47	0.56	− 0.14
Ecdamage	0.64	0.41	1	0.72	0.73	0.76	0.71	0.11
Agglom.	0.88	0.51	0.72	1	0.99	0.98	0.98	− 0.03
Urb	0.89	0.53	0.73	0.99	1	0.98	0.99	− 0.03
GDPcap	0.83	0.47	0.76	0.98	0.98	1	0.96	0.02
Trend	0.90	0.56	0.71	0.98	0.99	0.96	1	− 0.07
Dmgcap	− 0.07	− 0.14	0.11	− 0.03	− 0.03	0.02	− 0.07	1

Table 5
Effect of urbanization, agglomerations and GDP per capita on the number of occurrences.

Coefficients:	Estimate	Std. error	z-value	Pr(> |z|)	Exp(coeff)	1-exp(coeff)
(Intercept)	9.48 ***	5.97E − 01	18.63	< 2e − 16	13,108.28	–
Agglomerations	(7.73) *	4.13E − 03	7.858	3.90E − 15	0.000441	0.999559
Urb	(14.19) ***	1.84E + 00	− 12.448	< 2e − 16	0.000001	0.999999
GDPcap	(0.00) ***	1.19E − 05	− 19.33	< 2e − 16	0.999773	0.000227
Trend	0.16 ***	5.84E − 03	31.738	< 2e − 16	1.175272	(0.175272)

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1.

Table 6
Effect of urbanization, agglomerations and per capita GDP on affected population.

Coefficients:	Estimate	Std. error	z-value	Pr(> |z|)	Exp(coeff)	1-exp(coeff)
(Intercept)	27.04	5.97E − 01	18.63	< 2e − 16	5.54E + 11	–
Agglomerations	(30.1)	4.13E − 03	7.858	3.90E − 15	0.0000000000001	0.99
Urb	(18.8)	1.84E + 00	− 12.448	< 2e − 16	0.0000000067078	0.99
GDPcap	(0.0002)	1.19E − 05	− 19.33	< 2e − 16	0.99975892906	0.0002
Trend	0.21	5.84E − 03	31.73	< 2e − 16	1.2308438609971	(0.23)

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1.

Table 7
Effect of urbanization, agglomeration and GDP per capita on per capita economic damage.

Coefficients:	Estimate	Std. error	z-value	Pr(> |z|)	Exp(coeff)	1-exp(coeff)
(Intercept)	3.20	1.68E + 01	0.191	0.849	24.56	–
Agglomerations	(3.44)	6.71E + 01	− 0.051	0.959	0.032001	0.96
Urb	(12.90)	5.61E + 01	− 0.23	0.818	0.000002	0.99
GDPcap	0.00.	4.06E − 04	0.93	0.352	1.000377	− 0.000377
Trend	0.01*	1.37E − 01	0.06	0.952	1.008277	− 0.008277

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

In Table 7 we estimate the effect of urbanization, agglomerations and GDP per capita on the economic damage per affected person associated with each disaster. In this case the estimated impacts are lower than in the previous two cases, but the effects are still very important. An increase of 1% in the percentage of agglomerations and urbanization would reduce the expected per capita economic damage by 96% and 99%, respectively. As before, the impact of GDP per capita on the dependent variable is very small.

We may interpret our findings from statistical data, correlation and regression analysis concisely as follows:

- urbanization in a country is negatively related to damage
- population size and damage are positively correlated
- density of population has the same sign direction as population size
- population growth is negatively related to damage
- each disaster declaration is associated with an increase in agglomerations, urbanization, and GDP per capita at the world-scale level
- the number of affected people and the associated economic damage are also positively affected by the same variables, but with a substantially smaller effect than in the case of disaster occurrences
- for each declared disaster an increase of 1% in agglomerations and urbanization will reduce the expected impact on affected population by a magnitude of 99%.

5. Discussion on urban resilience patterns after an external shock

Our empirical research results show that the number of natural disaster victims is higher in countries with a larger population size and a higher density of population. To some extent, economic damage appears to be more substantial in countries with a higher population size and a higher degree of urbanization. Up to a certain level, the economic damage caused by natural disasters, is more affected by the degree of urbanization than by population size or density of population. This pattern may be observed in particular in developed countries. It goes without saying that density, size and disaster damage in urban areas are also co-determined by the urban prosperity level. A further analysis would require more fine-grained data on all these variables.

Urban agglomerations have an expensive and vulnerable infrastructure and a massive concentration of humans, business, houses and office infrastructure. Consequently, any disaster will have a dramatic effect on the socio-economic position of an agglomeration, if affected by an external shock. The long-run consequences are likely also determined by local cultural attitudes and effective policy responses. But it is also important to realize that the contribution of a modern and up-to-date urban infrastructure – in combination with external economies of density, proximity and connectivity – may reinforce the long-range socio-economic progress potential of a city. Efficient recovery and resilience may even improve in the long term a city´s position. This paper sets out to trace the determinants of urban recovery patterns after an external shock. We may therefore – on the basis of our tentative findings – hypothesise that the urban resilience trajectory – after an external shock – may have the following shape (Fig. 8), which is influenced by various moderator variables, viz.:

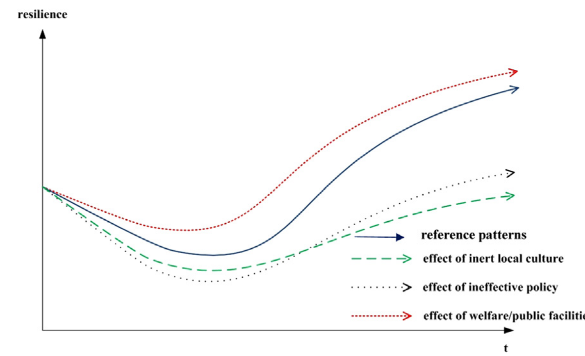


Fig. 8. Urban resilience trajectory after an external shock. [9]

(i) current level of high welfare and appropriate public facilities;
(ii) inert local cultural attitudes on urban management;
(iii) ineffective or delayed policy response after a shock.

Testing the validity of the constituents of the urban resilience curve as presented above in Fig. 8 has to be based on extensive panel data mining over a long time period and varied case study research, which may provide useful strategic insights regarding the drivers and effects of urban catastrophic events. In this context, institutional support systems and involvement of relevant stakeholders may also play a critical role. Cities may be able to plan and respond better, if the location and nature of risk is known and clearly mapped out, and also if risk assessment and management is mainstreamed in urban development and management programs. In the following figure (Fig. 9) which is an extension of Fig. 2, and is based on our findings and lessons, we present a comprehensive approach to urban resilience based on urban risk management and urban assessment and identification, and with an integral involvement of communities and relevant stakeholders.

Urban risk assessment, identification and management is ideally based on accessible and operational data. Clearly, the collection of necessary data, their integrity and the capacity of exploitation and interpretation of data in different formats, seems to be problematic in many cities. Collecting reliable, accurate and timely data remains a daunting task in many cities. Even if the data is available, it may rest with different organizations or agencies using different data formats. Risk identification requires a systematic inventory of past events, risk monitoring and forecasting, and dissemination of information on risk and response regarding risk groups and managers [45]. Specialized technical skills are inevitable. Although existing technical capacity can be used for undertaking a primary level of urban risk assessment (with some training), specialized technical skills are required for components of higher-level risk assessments such as flood or seismic risk assessment. Risk assessments require a proper financial allocation. While the primary-level of urban risk assessment would require minimal financial resources, the associated costs of the tertiary level can be beyond a city's budget for developing urban-management tools. Specific resources will have to be identified in order to initiate and sustain efforts

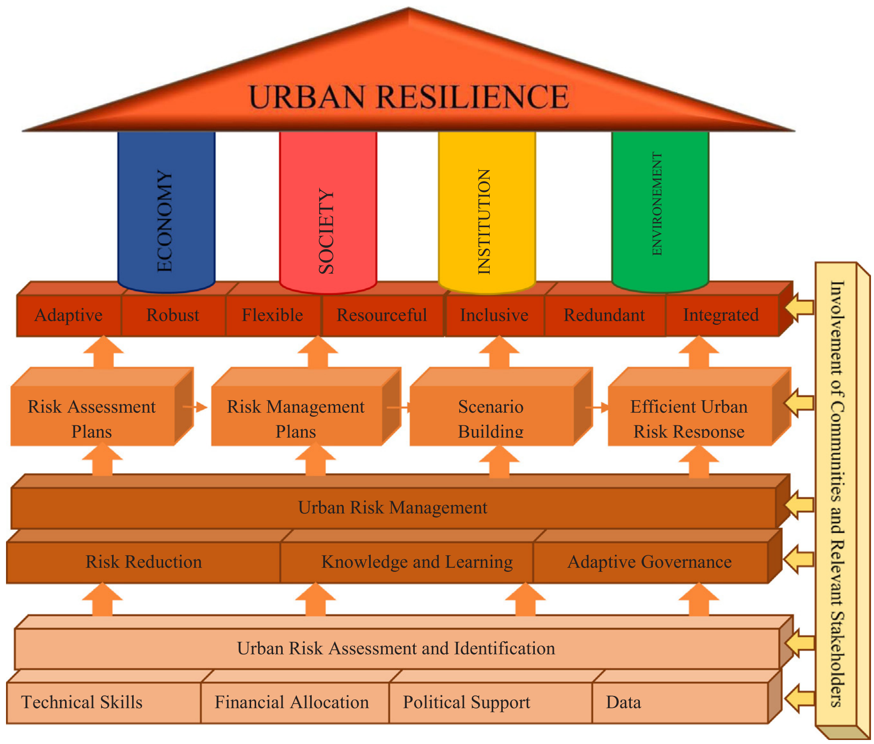


Fig. 9. Urban resilience based on urban risk assessment, identification and management. Own processing based on [14,16,33,35,37,41,45,46,51,53,57,60].

toward risk assessment and risk reduction. Without gaining and maintaining political support, efficient risk assessment and management is not possible. It may be difficult to gain necessary political support to initiate and mainstream urban risk assessment. Priorities may change with a change of leadership, leaders may focus more on other pressing issues, and there may be vested interests in not disseminating results of a risk assessment to a city's population ([14] p. 34).

Risk management needs adaptive governance which might be understood as an ability to zoom in on practical outcomes, flexibility in organisational structures and management, and support for practical experiments. Risk management needs to incorporate local knowledge [1] and requires relevant knowledge and training in terms of risk reduction training, identification of barriers to adaptation and incremental improvement mechanisms. Consequently, risk reduction should be based on risk consideration and land use planning, policy and financial support for alleviating risk, public education on risk reductions and ability to access and influence risk knowledge [45,46,60]. Involvement of communities and relevant stakeholders is essential for an efficient process of urban risk assessment, identification and management. Communities and relevant stakeholders may fill the gap in data gathering. They should be involved by the preparation of plans for urban risk assessment and reduction as well as in scenario building. Communities play also a very import role in case of disaster response.

Step by step, through efficient urban risk assessment and identification and proper urban risk management it is possible to design an "umbrella" concept of urban resilience interlinking main drivers and building blocks of resilience.

Although there is evidently a general overall link between population size and density, this phenomenon is not universally valid. The urban fabric is simply too complicated to draw unambiguous and incontestable inferences on the interlinked pattern of size, density, nature of disaster and damage costs, in relation to developed and developing countries. Clearly, much caution is needed in comparative studies. Of course, big and wealthy cities have normally a costly infrastructure, so that disaster occurrence may lead to high damage. This is evidently an empirical question that deserves solid applied investigation, in particular in the context of both prevention and recovery strategies.

6. Concluding remarks

The issue of the recovery potential of a city after an external disruption will most likely become one of the most serious challenges for urban policy in the future, given the rising threats caused by extreme weather conditions, population dynamics and wars/terrorism. Flood disasters (like the Dutch 'Watersnood-ramp' (Flood disaster 1953), Hurricane Katrina (2005) or Superstorm Sandy (2012)) will no longer be exceptions, but will form a regular part of the climatology on our earth, which tends to cause an increasing number of fatalities and natural disasters for cities in the future.

Prevention and abatement of such natural catastrophes (or, in general, external shocks) is fraught with many difficulties. Analytically, there are different strands of research and literature addressing these issues. One strand of scientific investigation is inspired by the theory of self-organising systems, and views cities or regions as dynamic learning agencies, which may return to their original equilibrium after a smart adjustment. This may be an elegant way to map out ex post abatement strategies, but this analytical approach has only a limited relevance in case of preventive policies. A second strand of literature is based on the theory of dynamic control and employs cybernetic steering mechanisms to cope with jumps that may bring a system out of equilibrium. This calls for more top-down oriented policy interventions. A final strand research which has attracted in recent years much attention – especially in the context of proactive and preventive decision strategies – is based on interactive dashboard mechanisms (see [31, 39]). In the latter case, the resilience capacity of a city is based on a merger of internal adjustment mechanisms and external policy handles, which are mutually interconnected. The dashboard approach – often presented as part of a smart or intelligent city policy – may be seen as a variant of enabling policy theory, in which an attempt is made to experiment with – or to simulate – possible or expected system's outcomes after an external shock (sometimes in the form of a scenario or virtual reality scheme). In the latter case, the attention is in particular focussed on the critical threshold conditions of an urban system (e.g., by assessing its carrying capacity vis-à-vis external shocks).

Which lessons can be drawn from the previous analysis? Our exploratory empirical approach has shown that natural disasters may have fatal consequences in terms of victims and economic damage. Countries with a higher density of population and overall higher population size show a higher vulnerability pattern, while the degree or urbanization shows a higher vulnerability pattern in terms of economic damage, but not inevitably in terms of number of victims. This pattern may be observed particularly in developed countries due to expensive and extensive infrastructure, especially in urban agglomerations. Preventive and proactive protection against the consequences of natural disasters offers – the same as protection against rain – the "umbrella" concept of resilience. Resilience of cities can be perceived as a "roof" or "umbrella" of an urban system that is formed by four main pillars – economy, society, institutions and environment – and these pillars stand on the foundation stones of adaptability, robustness, flexibility, resources, inclusiveness, redundancy and integration. The comprehensive approach to urban resilience based on risk assessment, identification and management proposed in this paper serves to depict a feasible or desirable urban resilience pattern after an external shock.

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