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Assessing and mapping urban resilience to floods with respect to cascading effects through critical infrastructure networks

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A R T I C L E I N F O

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A B S T R A C T

The urban environment is very concerned by network failures. These failures are propagating risks in area generally considered as non-vulnerable. There are various causes of possible disruptions in critical infrastructure networks (CIs), such as natural hazards, technological hazards, accidents, human errors and terrorism. However, in the last years it became harder to identify the possible failures of complex networks and to forecast their effects on the urban environment. New challenges such as climate change and the ageing of CIs are likely to increase the difficulty to secure the lifelines, raising the potential of damages and economic losses caused by failures. This paper suggests some new methods to assess and map resilience levels to floods taking into account critical infrastructure networks as risk propagators at different spatial scales. The conclusions support the development of innovative strategies and decision support systems for new resilient urban environments.

1. Introduction: Human-made disasters and cascading effects

In a global changing – and warming – context, natural disasters have increased of about 2% a year in the world over the past 15 years [7]. Summer 2017 is a representative example of the accumulation of natural disasters in a very short period of time. Mid-August 2017, Hurricane Harvey reached Caribbean and Texas. This category 4 hurricane (out of 5) caused more than 80 deaths and heavy economic losses in this oil region, with many days of torrential rains. The Gulf of Mexico did not really have time to recover: Irma breaks after Harvey, with winds of more than 290 km/h. This category 5 hurricane almost completely destroyed the French islands of Saint-Martin and Saint-Barthélemy. The damage costs were estimated at 1.2 billion euros by the *Caisse centrale de réassurance* (CCR) [6]. Mid-September, Hurricane Maria reached Dominica, eastern Caribbean (two weeks after Hurricane Irma), northeast of the Bahamas and Puerto Rico. It caused a hundred deaths and the damage costs are estimated between 15,9 and 95 billion dollars. This accumulation of disasters in a very short time period highlights a global climate deregulation [23]. If those examples remain extremes, we observe an increase in the "daily disasters".

Among these disasters, the risk of flooding causes the most destructions [46]. Indeed, since 1960, the number of floods has increased considerably, reaching more than 600 events for the year 2007 [48]. For example, in 2013, we observed that flood damages were approximately 50% higher than in the period 2003–2012 [33]. Although the number of deaths has decreased in the face of this risk, floods are still the costliest natural catastrophe, with a total volume of 100 billion €/year by the end of the century.

At the same time, the increasing complexity of cities makes flood risk management difficult. Over the last ten years, half of the world's population has become urban. Human concentration (50% of individuals living in urban areas [48], and urban population makes flood risk management very difficult in such areas. Urbanization of urban areas has increased from 10% in the 1990s to 50% in just two decades [24]. This very rapid process has weakened the territory because cities are not prepared or equipped to manage the needs of such a concentration of population, especially when a risky situation appears. This, due to a lack of available land, comes to settle in the risk zones. These spaces left free are gradually nibbled by urbanization without respecting the natural functioning of catchments, rivers… leading to impervious soils, preventing the necessary infiltration of rainwater. Also, the increase of man-made disasters - an increase in frequency and intensity - makes these territories even more fragile and complex to manage. It is therefore established that, in urban areas, man-made risks tend to have extreme consequences [30] especially because issues are concentrated in vulnerable areas. Besides, these areas are increasing because of urban sprawl.

Among the urban equipment, some infrastructures are more essential than others, namely Critical Infrastructure (CI). It is a hard task to define what "critical" infrastructure exactly means. Etymologically,

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critical comes from ancient Greek *kritikos*, word linked to the vocabulary of crisis, derived from the verb *Krinein*, meaning "separate" or "decide" or "choose" [38]. These infrastructures concentrate all the functions [32] which are necessary for the functioning of a community. They are considered as "critical" because their potential destruction could weaken the whole defense and economic organization [16] of a country or a city. Critical Infrastructures can be natural; water supply, flood water storage; built, energy networks, telecommunication networks, emergency services, transport networks; or virtual, cyber information systems for instance [16,38]. Nevertheless, none exhaustive list exists to explain what is a critical infrastructure.

Cities are developing links between people, activities, properties, infrastructures and networks and create by this way a quality of life and dynamic activities. However, the density of urban creates new risks. The lack of available lands results to build new infrastructures in risk areas [38] and, moreover, this sprawl leads to an over-interconnection between technological networks and society. These links have increased the vulnerability of urban areas, building an interdependence [32] between all urban factors. The complexity of infrastructures and urban systems weakens the functioning of components in a time of crisis. Because of the interconnected system, if a shock happened, the system would crash more often since the dysfunctional phenomenon would be more important than the first affected area [38]. It appears that, the more a territory is connected, the more the impacted area will be important [22]. Because of the concentration of activities, networks and populations, the spread of risks is very quick and disrupts large-scale territories. The main difficulty is that experts cannot precisely predict the potential breakdown of infrastructure or its domino effects [33,5]. As we cannot predict these events, traditional crisis management is ineffective in case of infrastructure breakdown [5]. Prevention and planning management are not suitable in the way that these strategies do not take into account the dynamics of threat, and therefore the dynamics of interdependences [38]. But the very own definition of crisis and its consequences, is that its unpredictable, in permanent changes and evolutions. That's why, for more than ten years, experts have begun to question themselves about their risk management. In policy, economics, urban planning, architecture and scientific research the focus is now increasingly focusing on strategies to make urban systems simultaneously less vulnerable and more resilient to climate-related disasters, while addressing the long-term challenges of sustainability and quality of life [34]. The injunction of international authorities to find a new risk management (system) able to create a transition to a general culture of risk [14] led researchers and managers to look at other approaches to manage natural hazards. A new approach has thus been gradually integrated, based on the concept of urban resilience.

The goal of this article is to present new methods, in a way to better understand urban risk propagation through CIs breakdowns and to reduce vulnerability of network interdependencies increasing urban environments resilience. We will define in a first part what "cascading effects" and "risk propagation" exactly mean. In a second part, we will describe how we used the concept of resilience to design some methods and tools, thanks to a research-scientist collaboration and managers of the territory, to improve the resilience of urban environment to floods. Finally, we will present two possible applications in Hamburg (Germany) and Avignon (France).

2. Cascading effects and risk propagation

Globalization created a connected world, an imbroglio of policies, economies, procedures and expectations. These interactions between territories and societies are complex and create interdependencies [38]. However, these interdependencies create as much wealth and security as they weaken the territories and their populations in case of risks. As urban areas are interconnected, an infrastructure breakdown will impact territories beyond geographical and functional borders [5]. As they are connected and dependent on multiple levels, CI may impact much more than their first impact territory. The evolution of the impacted area can be caused by cascading effects, effects which increase the impacting area, generating secondary effects [32]. For example, urban networks can increase the risk, propagating water into large areas. Major floods can impact a specific area but as networks are interconnected, the risk will reach other territories which should not be flooded [22];. Besides, some crisis consequences are not caused by physical and direct damages but by the interruption of activities. Failure of electricity system can damage perishable goods, road deterioration can prevent relief from reaching an area, aggravating the danger of the populations, and complicate first responder operations.

Urban networks failure is a good example to understand and measure what a breakdown of CI can be. Urban networks are an essential part of the urban system. In an interconnected world, urban networks connect more and more people and territories, offering an important variety of resources and opportunities but also creating complex situations of interdependence. Public transport, electricity networks, gas, telephone, heating, waste, etc., make the urban system management more complex and delicate [38]. If they are essential to create dynamics, relationships, economies, these networks are also extremely vulnerable. Because of their interconnectivity, all urban operations depend on them. A single failure can have cascading effects and impact the entire network and, because of (a) reticular urban system, the entire city.

Consequences of Hurricane Sandy in New York City are a good example of these extreme vulnerabilities aggravated by CI breakdowns. Hurricane Sandy, one of the largest hurricanes ever recorded in the Atlantic [26], emerged off the west coast of Africa on October 11, 2012 and moved over the Gulf Stream. Sandy created a storm surge with highest values in New York City and its harbor, causing the destruction of part of the electricity grid: destroyed air lines, flooding of the buried network, etc. Flood impacts included flooding of subways (Fig. 1; the Long Island Rail Road remained closed until November), road tunnels, and the three major airports.

The New York University Langone Medical Centre was evacuated after the breakdown of generators due to flooding, causing the transfer of 200 patients. The destruction of power networks left 21,3 million people without electricity and the failure of electrical system caused fires which destroyed 111 houses and damaged 20 others [20]. Daily life was severely disrupted, with the interruption of the metro, the breakdown of the heating network, security systems, telecommunication services. In addition, alternative solutions such as emergency power generators have not been able to operate, refineries being in short supply and unable to provide the necessary fuel. If direct damages were estimated at 32,8 billion of repairs and restoration, indirect losses have cost much more for city and citizens. Due to interrelated networks and activities, indirect losses are caused by disruption of CI, such as

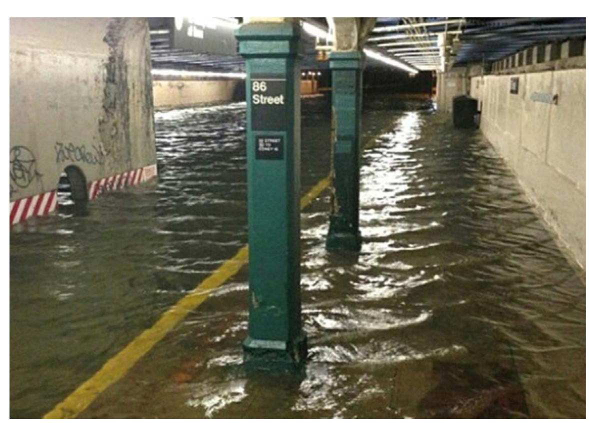

Fig. 1. Port Jefferson, NY.
Source: Newsday