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Urban resilience: From a limited urban engineering vision to a more global comprehensive and long-term implementation

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Abstract :

This paper presents a research project spanning over 15 years, dealing with territorial resilience to flooding. This paper presents a global retrospective view on how research on the concept of resilience began with a primary focus on critical infrastructure resilience networks. These infrastructures are always identified by experts as an aggravating factor leading to territorial systems disruptions. The focus on critical infrastructure resilience networks served as an important first step to improve knowledge on mechanism failures and their impacts on communities. However, this first step was insufficient in providing more resilient systems and territories to floods. Today, other approaches are useful for implementing strategies of resilience to answer city managers' needs, such as organizational strategies, including participative tools. Long-term resilience is addressed within this research for territorial resilience monitoring and planning. This article is primarily based and illustrated on the research, projects and scientific advances conducted by the authors.

Highlights

► This article defends the usefulness of the concept of urban resilience as a risk management tool. ► It presents two approaches to operationalizing the concept of resilience, a technical-functional approach and an organizational approach. ► The technical-functional approach is developed around the issue of critical infrastructures and urban networks. ► The organizational approach is analyzed through indicators of global, social, urban and technical resilience. ► The originality of the article is that, after analyzing these approaches, it concludes on the problem of the multitude of methodologies that aim to operationalize resilience, including a resilience observatory.

Keywords : Urban resilience, Critical infrastructure, Spatial decision support systems, Resilience assessment, Observatory

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1. Introduction

In a context of climate change, urban areas are facing an increase in the recurrence and intensity of disasters. Among these disasters, floods have impacted up to 2 billion people over the period 1998-2017 (European Environment Agency, 2017). Faced with these challenges and related uncertainties, urban areas are increasingly vulnerable to urban networks disruption risks. These disruptions can therefore produce cascading effects, impacting areas that were originally not at risk or vulnerable (Boin and MacConnell, 2007). These service disruptions weaken urban areas and activities and raise questions about risk management. Risk management in itself has had to evolve in order to adapt to these "new" risks and uncertainties related to climate change and the concentration of issues (economic dynamics, buildings, infrastructure, assets, social dynamics, political trends, etc.) in urban areas. The concept of resilience has therefore been gradually integrated into risk management in order to prepare territories and populations for the increasing hazards and their consequences to relaunch an activity. Resilience has been integrated into risk management since the 2000s (Campanella, 2006), but it is still an unclear concept today and poorly integrated into risk management strategies. A variety of definitions exist today in hopes of clarifying the concept of resilience (Meerow et al., 2016). Belonging to multiple disciplines (Alexander, 2013), resilience in risk management can at the same time be related to capacities of resistance to shock (Serre, 2018), absorption (Cardona, 2004), adaptation (Pelling, 2003), reactivity (Pickett et al., 2004), reconstruction (Walker et al., 2004), learning (Carpenter et al., 2001; Klein et al., 2003), rebound (Davoudi et al., 2012), etc. The main idea is that a system (Sayers et al., 2013) is resilient if it recovers from a shock by limiting the negative impacts (Butler et al., 2014) and subsequently restarts activities. Defined as the capacity of a territory and its population to plan for, adapt, absorb, recover from, learn and evolve (UNISDR, 2009; Cardona, 2004; Pelling, 2011, Walker and Salt, 2006; Carpenter et al., 2001; Klein et al., 2003; Davoudi et al., 2012), resilience has to address all territory components in order to analyze its risk reaction. However, the current understanding and operationalizing of the concept of resilience is

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limited and remains an important issue which must be addressed. This research is principally divided into two approaches, a technical-functional approach and a more organizational approach (Serre, 2018; Serre et Heinzlef, 2018; Heinzlef et al., 2019).

The technical-functional approach focuses on assessing the resilience of critical infrastructure, which concentrate all urban functions (Escarameia and Stone, 2013; Kunz et al., 2013; Pescaroli and Kelman, 2017; Pescaroli and Nones, 2016) and their ability to withstand and recover from a disruption. These critical infrastructure are considered essential for the political territory well-being and territorial dynamics. It includes infrastructure such as telecommunication, energy transport networks, emergency services, critical buildings (hospitals, defense institutions, etc.), water and food supply, cyber or economic interactions, etc. Among these critical infrastructure, urban networks illustrate and concentrate several issues. In order to improve the resilience of cities, technical networks have already been identified as entry points for failures (Serre, 2018; Lhomme and al., 2013) and therefore constitute the systems on which technical and management measures will focus. Indeed, networks behave both as propagators of failure through their geographical extension and interdependencies, and are at the same time essential for reconstruction (Serre, 2016). Networks are thus the nervous system of the city in which the slightest failure can have significant consequences on the entire urban system (Gonzva et al., 2017). Assessing the urban technical networks resilience therefore appears to be a critical step to increase cities' resilience, to guide the responses to reduce the effects of floods such as network improvements, evacuation recommendations, prioritization of interventions, etc. (Robert et Morabito, 2009: Macnally et al., 2007).

The organizational approach seeks to approach resilience from a more general analyse perspective than technical-functional resilience (Toubin et al., 2015; Heinzlef et al., 2019; Heinzlef et al., 2020a). Resilience is a comprehensive and multidisciplinary approach that integrates many social and territorial elements, both tangible, such as critical infrastructure, buildings and so on, and intangible, such as cultural aspects (Asprone et al.,2014; Heinzlef et al., 2019). Assessing the resilience potential of an organization or territory is necessary to mobilize managers in order to lead to the anticipation of disruptive events and the planning of management measures. The idea is to understand all the elements that promote resilience, namely, a better response from critical infrastructures, the built environment, managers, local actors and residents in order to cope with a disruption and restart an activity and a dynamic in response to it (Heinzlef et al., 2019).

The objective of this article is to present the methodologies and results coming from these two main approaches, namely the technical-functional and organizational approaches, leading to a clearer urban resilience operationalization . Faced with various limitations raised by current studies, this article proposes to develop the contribution of new techniques and research perspectives, in particular through the development of spatial decision support systems under the form of a Resilience Observatory. The first portion of this article presents the challenges of urban flood risks and the vulnerability of critical infrastructures. While the second and third portions describe different approaches based on the technical-functional analysis of resilience and the advantages and limits of organizational approaches, respectively. The final portion presents the perspectives of authors focused on the Resilience

Observatory project in order to respond to the challenges of planning and decision-making processes in risk management strategies.

2. Vulnerable infrastructure: a critical issue for flood risk management

Urban areas concentrate economic, political, human, technical and urban challenges on increasingly limited geographical areas. Areas that are becoming increasingly vulnerable to the climate disasters. Among these urban areas, some infrastructure are more or less essential to the functioning of the territory. These critical infrastructure (CI) concentrate all the main functions which are necessary for the proper functioning of a territory (Serre and Heinzlef, 2018). These CI can represent systems, facilities, technologies, networks, assets and services essential to the health, safety, security or economic well-being of inhabitants and the effective functioning of government (Fig 1).

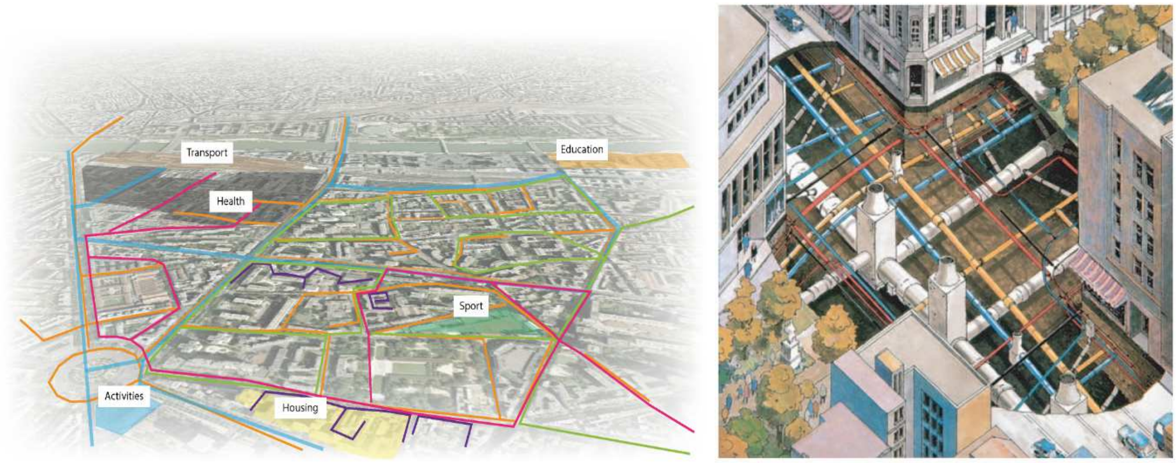


Figure 1. Critical infrastructure network as a support of urban life (Serre, 2013)

Critical infrastructure can be stand-alone or interconnected and interdependent. Most of these critical infrastructure interact, however, these interactions are often complex and unrecognized because they transcend the geographic, political, cultural and organizational boundaries of the systems (Fekete et al., 2015). For example, the fall of the World Trade Center towers in New York in 2001 caused, among other things, a breakdown of the web in South Africa, Germany, Italy and Romania. Disruptions of critical infrastructure could result in catastrophic loss of life, adverse economic effects and significant harm to public confidence. These interdependencies then play the role of a risk diffusion factor (Lhomme et al, 2013). According to the concept of the domino effects (Bach et al, 2013; Galland, 2010; Nones and Pescaroli, 2016; Pescaroli and Nones, 2016), i.e. a chain reaction causing changes in a territory, some areas come to be impacted by the disaster, even if they were not located in the same area directly in the flood hazard extension zone. Among these CI, urban networks are a good example. In an interconnected world, urban networks connect more and more people and territories and offer a wide variety of resources and opportunities. However, they also create complex situations of interdependence. Public transport, electricity, gas, telephone, heating, waste, etc. make the management of the urban system more complex (Serre and Heinzlef, 2018). While they are essential for creating dynamics, relationships, economies, these networks are also extremely vulnerable in the event of a crisis. On account of their interconnectivity, all urban operations depend on them (Serre, 2018). A single failure can have cascading effects and disturb the entire network, and because of the reticular aspects of urban systems, the whole city (Serre, 2016). Therefore, some damages are not caused by direct physical damage, but by the interruption of activities supported by critical infrastructure (Heinzlef et al., 2020a). A distinction is made between direct and indirect impacts (Nones and Pescaroli, 2016). Direct impacts are directly caused by the disaster and may refer for example to damages to physical elements (furniture, buildings, stocks, equipment, etc.). Impacts become indirect when they are not caused by the disaster itself. Indirect impacts can be related to the interruption or damage of critical infrastructure service.

The dependencies of a city which relies on critical infrastructure increases the vulnerability of cities to risks aggravated by the emergence of "new" risks and uncertainties. To face such a challenge, risk management is beginning to evolve, especially in integrating the concept of resilience. As a concept with multiple interpretations, resilience remains complex to operationalize and integrate into risk management strategies, at least at local scales. Several methodological approaches have emerged in order to respond to these limits of appropriation. Among these approaches, critical infrastructure interdependencies were useful to first increase knowledge in this area.

3. Modelling critical infrastructure networks interdependencies: a partial view of urban resilience

This part is partly based on an approach we designed within a European FP7 project namely FloodProBE and described in this report (FloodProBE, 2013):
http://www.floodprobe.eu/partner/assets/documents/Floodprobe-Deliverable-Report_task21_4March2013.pdf

We invite the interested reader to read this report for a full presentation of the step wise approach we developed. Below we present only the most advanced step to integrate critical infrastructure networks interdependencies unpublished in scientific journals at this time. This corresponds to step 4 only of the figure 3.

Most critical infrastructure systems interact (Peerenboom, 2001) through direct connectivity, policies and procedures, or geospatial proximity (FloodProBE, 2013). The modelling and analysis of interdependencies between critical infrastructure elements is a relatively new and very important field of study (Pederson et al., 2006). It illustrates common representations of infrastructures based on the scenario of a flooding event and the subsequent response. There are ties and dependencies within each infrastructure and between the different sectors. The solid lines in crossing sectors and connecting nodes represent internal dependencies (Fig.2), while the dashed lines represent dependencies that also exist between different infrastructures (infrastructure interdependencies) (FloodProBE, 2013).

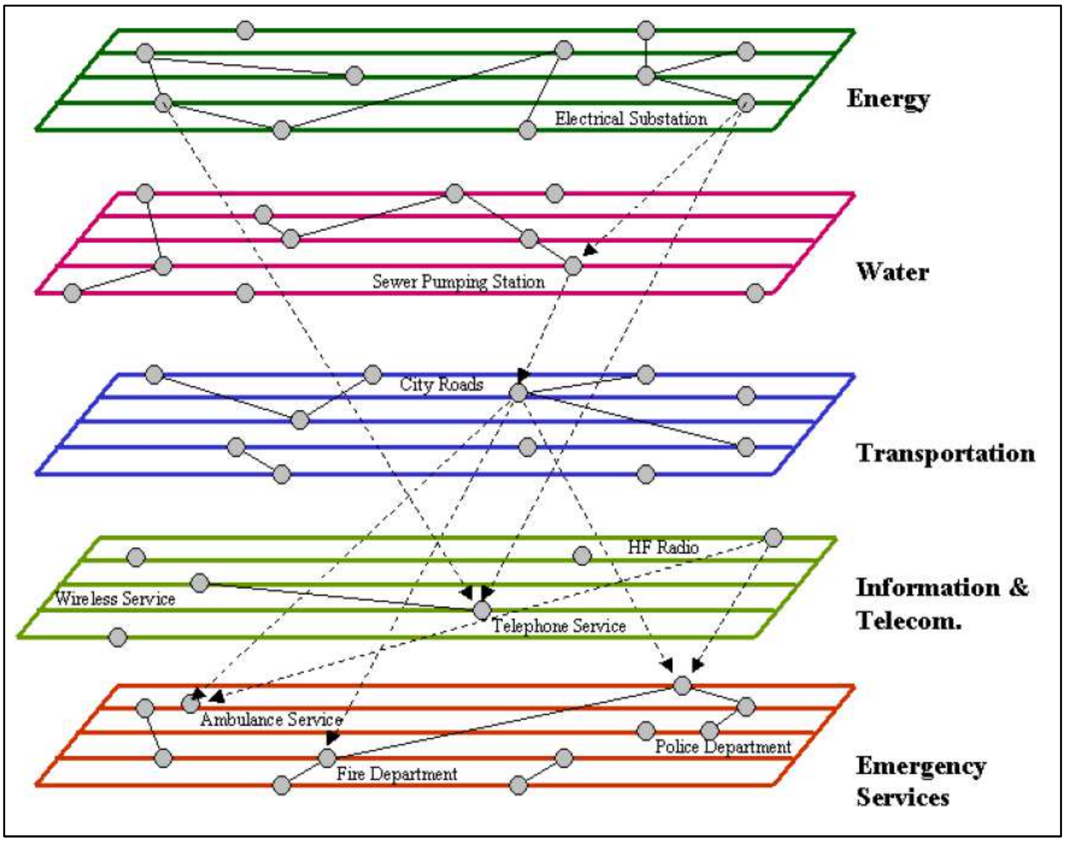


Figure 2: Critical infrastructure interdependency modelling (Pederson et al., 2006)

The failure of one CI may cause disruption in others. For instance, the utility of traffic control in a municipality is generally provided by a system of three CIs - power grid, telecommunication network, and traffic control boxes. However, the proper functioning of the three CI system components is only a necessary condition for the normal operation of the traffic control system. It alone is not sufficient. The criteria for the connections between the three ICs, such as the nature and extent of their bonding or the self-regulating and management mechanisms, are essential elements for the proper functioning of the traffic control system, but only exist when the three ICs are interconnected (McNally et al, 2007).

CI can be considered as complex systems which can be defined as follows: ''*Traditionally, a system is said to be complex if its attributes are commonly out of the norm, as compared with other systems. Complex systems are characterized by having a large number of dimensions, nonlinear or nonexistent models, strong interactions, unknown or inherently random plant parameters, time delays in the dynamical structure, etc.*'' (Jamshidi, 1983). Additional characteristics of complex systems are an adaptive emergent behavior and feedback loops.

CIs can be described as a ''system-of-systems''. 'A system-of-systems (SoS) consists of "*multiple, heterogeneous, distributed, occasionally independently operating systems embedded in networks at multiple levels, which evolve over time*'' (DeLaurentis, 2003). Alternatively, system-of-systems can be defined using the term ''complex systems'': ''*Systems–of-systems are large scale concurrent and distributed systems that are comprised of complex systems''* (Kotov, 1997). The questions are: how to deal with the complexity? And how to model such systems?

Consequently, it is important to draw distinctions between two related but different concepts - a CI system, and a system of CIs (Hall et al., 2013). A CI system is an assemblage of functional objects (Fratini et al., 2012) that provides a certain essential good or service. A power supply system, for example, provides electrical service through the synergistic interactions among its components - the power plant, substations, transformers, and transmission and distribution lines. At the same time, a CI system is also a part of an even larger system - a system of CIs, which offers a range of public goods and services through the collaborative operations of (or interdependencies among) its individual CI system components. The behavior of a system of CIs, as a manifestation of the usually complex interdependencies, cannot be fully described and understood by the behaviors of its CI system components (Rinaldi et al, 2001).

In the case of flooding (Hoang and Fenner, 2016) it is essential for the functioning of the society to know where are the weak points in urban infrastructure networks (FloodProBE, 2013). This knowledge is essential for flood risk management and mitigation measures. Some municipalities and other local governments are already well prepared and have a running flood risk management plan; others have not even started the dialogue between the many people and institutions which are responsible in the case of flood events. The stepwise approach provides a guide for risk assessment from a basic to an advanced assessment process (Fig.3).

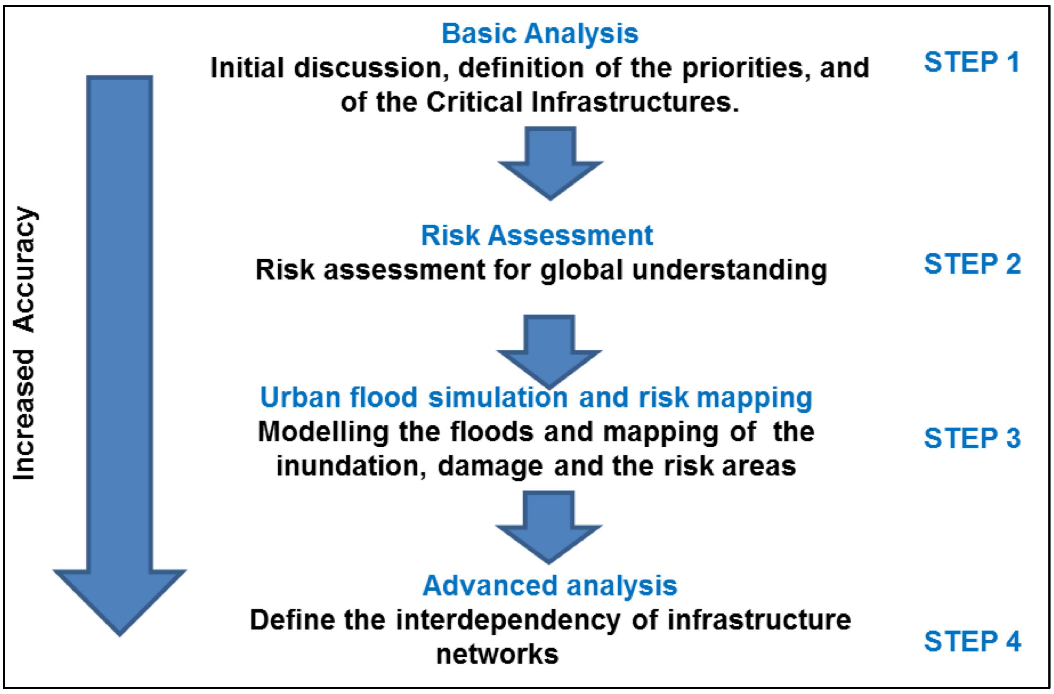


Figure 3: Framework for risk assessment (Lhomme et al.,2012)

Starting with simple generic risk analyses, continuing with a computer based tool showing the weakest infrastructure asset in a municipality, including existing urban flood simulation and risk mapping and concluding with GIS based numerical model and risk mapping provides the framework support in the entire assessment process (FloodProBE, 2013). The first two general approaches increase the awareness of the driving forces for flood risk management and mitigation. Step three; flood risk mapping, previously referred to as the "classical" risk assessment methodology until today, is an essential input for step 4 which shows the interdependencies between critical infrastructures, the weak nodes in the system and sub-system, and the cascading effects. All four steps can be run independently. Indeed, these steps are adapted according to the risk data of the different municipalities. Depending on their knowledge, skills, advances, tools, the analysis can either implement the 4 steps or develop some of them according to the needs. These steps do not depend on a chronological order but on expressed and observed needs. Deciding which steps are required depends on the aim of the user and of the outcomes of the first steps. However, if the first steps show that there are

CIs at risk from flooding, the latter two steps are needed to provide a full picture of the flood risks for CIs. It is an essential and crucial part, and its success mainly depends on the good will of the stakeholders. The last step can be difficult to understand and used by managers due to the over-technicality which complicates the urban managers' appropriation. Furthermore, an urban territory is composed by several components, integrating social dimensions (age of population, professional situation, habits, etc.), economic dynamics, land uses, etc.

Analyzing and understanding urban resilience needs to consider all these characteristics and elements in order to study the complexity of urban risks. Therefore, this primarily urban engineering approach must be processed with a more organizational and participative approaches to operationalize the concept of resilience (Heinzlef et al 2020a). To answer this issue, recent research on critical infrastructure interdependencies is taking three main directions:

- An engineering path leading to direct collaboration between experts and operators. This comes in the form of performance engineering, civil engineering and complex project engineering (Robert, 2009);
- The second path consists in developing collaborative approaches mixing modelling sciences and social sciences to better involve the majority of important stakeholders localized on specific territories (Heinzlef et al 2020b).

Finally, the methods we developed to model critical infrastructure networks interdependencies (Lhomme et al 2013) was a way to model the effects of flood propagation in cities as well as their consequences on a specific network and its cascading effects on others. Such a result is based on an urban complex analysis. Interested readers can consult (Serre et al. 2008, Bambara et al., 2015).

4. Achieving flood resilience through organizational answers: a more comprehensive approach

Faced with the limitations of a network-centric and technical-functional approach, a more global and comprehensive approach has been developed. This approach sought to address several pitfalls, namely the measurement and mapping of resilience, the visualization and understanding of the concept, and the appropriation of the concept by local stakeholders (Heinzlef et al., 2019).

4.1. Assessing resilience

A large part of operationalization consists in determining how a concept can be measured and selecting which indicators will be used to measure the concept in order to generate data about it (Adger et al., 2004). The assessment of resilience is therefore a matter of measurement and the designing of indicators (Dauphiné and Provitolo, 2007). The use of indicators has spread in the field of risk, the measurement of territories and populations vulnerability, and resilience to risks. One of the first arguments to build indicators is that by defining and characterizing a fuzzy concept, indicators raise awareness of complex issues among the scientific community, as well as the general public (Prior and Hagmann, 2014). Furthermore, resilience indicators can make major contributions to assessing community needs and objectives while aiding to set up resilience strategies (Cutter, 2016). By providing information on the territory, the risks and the level of resilience, these indicators make it possible to build new knowledge by raising the awareness of the populations and by accompanying the actors towards a transition towards more resilient risk management. These indicators, which are useful when designing a strategy, are also valuable for monitoring the progress of work, decision-making and progress made by a community. Measuring resilience has therefore become an international priority in order to build strategies to risk management (Winderl, 2014). The question of how resilience is measured is as old and important as the concept itself (Prior and Hagmann, 2014). Numerous indices and indicators of resilience have been developed in various disciplines (Freudenberg,2003). While some research has established global indicators (physical, economical and social indicators) on a national scale, others have favored a local scale at the infrastructure level by focusing on technical-functional indicators. Few researches have managed to reconcile the issue of decision support with a comprehensive approach to the concept of "local" infrastructure (Cuter et al., 2010).

In this context of organizational resilience, we developed three indicators in order to measure urban, technical and social resilience at a local urban scale (Serre and Heinzlef, 2018).

To address the issue of risks in urban areas, the choice was made to analyze resilience over a long period of time (before, during and after a crisis), and no longer by only following a shock (Heinzlef et al., 2019). This article has made it possible to understand the determining components useful for a resilience strategy design. This positioning has allowed for a deeper, more thorough conceptual framework for resilience. Thanks to the identification of these components, three indicators were designed as below (Fig 4.):

Figure 4: Resilience characteristics (Serre and Heinlef, 2018)

- An urban resilience indicator: urban resilience embraces all urban dynamics - physical such as buildings (age of the building, elevation,… for example) and critical infrastructure - or virtual such as economic dynamics. We have analyzed the influence zones of critical infrastructure within a 100m radius, access to medical infrastructure (in ten minutes), tourism and economic dynamics (business creation and disappearance) ;

- A social resilience indicator: social resilience is defined here as the ability of a population to adapt and recover from a disturbance. Several factors enable a population to act proactively, react and redevelop activities and interactions during and after a crisis. These factors may include age (calculation made, for example, on the ratio of the elderly to the total population), socio-economic status, education level, habits, government support, etc. In this analysis, social resilience is approached as a community resilience, not individual resilience;
- A technical resilience indicator: as previously established, urban networks are essential in the analysis of resilience. In this analysis, we integrate both the diversity of networks (the number of different networks within a 100 m radius and the accessibility of these networks (the length in meters of public roads to access these networks in the area).

The data for each indicator was 90% open source. After selecting the raw data, the data was transformed and normalized. In order to understand the frequency of each variable, each raw data item was transformed into percentages (Heinzlef et al., 2020). Each variable had a weight of 1. This unique weighting is explained by the desire to avoid disparities between variables (Fekete, 2009), as some of them are sensitive and subjective. Following this process, it was necessary to determine the normalization. Normalization allows a series of values (usually representing a set of measures) to be adjusted according to a transformation function in order to make them comparable at specific reference points. A min-max normalization was performed to illustrate variable which have a positive resilience impact (such as working people and young people) and variable which have a negative resilience impact (such as the very old or very young), where each variable is decomposed into an identical range between zero (worst rank) and 1 (best rank), to create indicators with similar measurement scales, and to compare them with the same set of measures.(Heinzlef et al., 2020).

This research answered the local challenges of defining and measuring resilience (Heinzlef et al., 2019). This research has been developed, tested and applied on the city of Avignon (France). A collaborative approach has enabled the results of the indicators to be put in place and led to long-term thinking to implement resilient risk management strategies. As the research had previously focused on technical-functional resilience, this part allows for the understanding of resilience through a more exhaustive prism including urban, social and technical characteristics in order to analyze territorial resilience in all its complexity. The challenge now is to work on the accessibility of these indicators in order to make them understandable, usable and reusable by different local actors in order to be able to produce a broader resilience index (Heinzlef et al., 2020b).

4.2. Mapping and visualizing resilience

Faced with a lack of integration of resilience models in risk management plans, we looked for a possible approach where the concept of resilience could better integrate future plans. After having constructed a conceptual model of resilience and three measurement indicators, it was decided to use geo-visualization techniques to operationalize the resilience concept (Kwan and Lee, 2003; Marzouki et al., 2017; Kurwakumire et al, 2019). Geo-visualization techniques group together visualization practices, mapping, data analysis and production, etc. in order to participate in decision-making (Nöllenburg, 2007). The processing tool (Feature Manipulation Engine) uses an interface instead of code lines, which makes the computer script more accessible and understandable (Heinzlef et al., 2020a). In addition, the accessibility, updating and reuse of data is promoted by 90% use of open access data (National Institute of Statistics and Economic Studies) (Heinzlef et al., 2020a). This willingness to "transmit" research beyond the study itself was reflected in the choice of open data and open access tools. In addition, this willingness to promote the results is explained by the fact that urban managers do not fully understand how to use the concept of resilience in their plans (Heinzlef et al., 2020b). Using known, free and accessible data helps to promote understanding and use of the established methodology. Open data and open access tools "liberate" knowledge and construct knowledge (Goëta and Mabi, 2014; Janssen et al., 2012). The interest of the method is expressed by the local scale modelling of the elements of urban, technical and social resilience, and the collaborative approach with local actors. (Heinzlef et al., 2019). This collaboration did not take place *a posteriori* to the design of the spatial decision support system but at each stage. Moreover, each step of the script, data used and results are easily understandable and accessible thanks to the choice of tools and data.

Most models do not make their processing or databases accessible. Resilience is also limited to a technical-functional analysis by integrating the impacts of domino effects. This research led to designing a spatial decision support system that enables the visualization, understanding and accessibility of treatments and results for local stakeholders (Heinzlef et al., 2019; Heinzlef et al, 2020b). The design was carried out in collaboration, allowing local actors to integrate the methodology, but also to share their expertise. The spatial decision-support system makes it possible to assess and map urban, technical, social and environmental resilience.

The challenge now consists in making these models accessible by changing the scales of analysis and the study area (sub-district, neighbourhood, city, networks, etc.). The idea is to think about a tool that allows for the confrontation of different scales thanks to a visualization that is easy and accessible for local actors.

4.3. Operationalize the concept of resilience through collaborative approaches

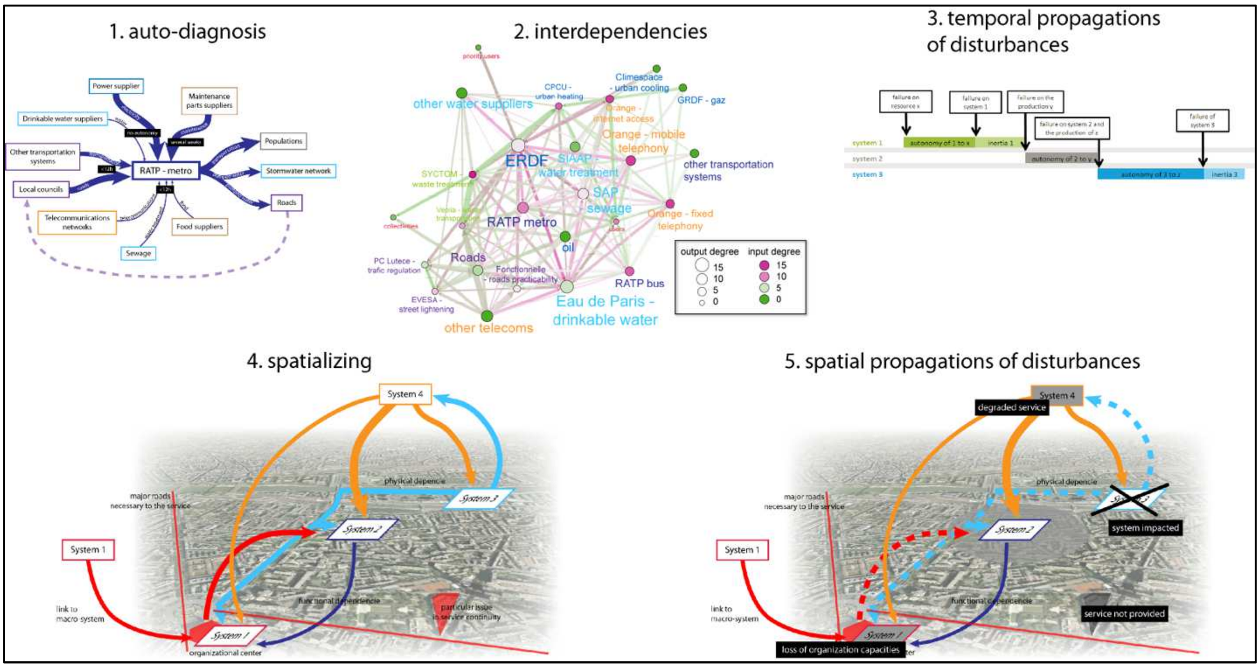
Involving "local" people or people directly concerned by the issues studied does not seem to be new and even less original (Toubin et al., 2015). The richness of having people from all walks of life interact allows for "exploring the world of possibilities" (Callon et al., 2001), enriching discussions, encouraging cross-fertilization of views on the same subject, to be both more measured and more incisive in a specific field. Resilience, a social and tricky concept, is therefore a subject that requires a confrontation of views, knowledge, scientific and practical knowledge, perceptions and interpretations. Nevertheless, despite the population being often the first impacted by natural hazards and their difficult management, the inhabitants (Kuhlicke et al., 2011) as well as the urban services (Toubin et al.2015), which are nonetheless actors most directly impacted, are not sufficiently involved. We defend the idea that the conception of a hybrid knowledge allowing the involvement of all actors of the territory, from inhabitants to managers via scientists and or facilitators, would allow the operationalization of urban resilience thanks to an appropriation of the concept and stakes of urban risks (Heinzlef et al., 2019).

It would therefore be beneficial to build this shared vision and commitment around the concept of resilience, an approach that would also allow a transition in the ways of conceiving the city and understanding risks in urban environments (Heinzlef et al., 2020b). We therefore propose to develop strategies for integrating resilience in a co-designed manner with city's stakeholders. This would allow their direct involvement, as well as the application of this strategy before or during a crisis (Serre, 2013). Involvement at the level of conception may guarantee the sustainable use of the resilience concept in flood risk management strategies (Heinzlef et al., 2020b).

4.3.1. Parisian case study

Toubin et al. (2015) developed a methodology to contribute to improving conditions of urban resilience and more particularly resilience of Parisian urban networks face to urban floods, based on the 1910 case study. Indeed, the Paris conurbation is exposed to the risk of major but infrequent floods. The inevitable occurrence of flooding is all the more worrying for the authorities as they see other major world cities hit hard, sometimes a few years apart, by similar events (New York or Prague, for example). The flood of 1910 is the focus of attention because it is rich in lessons for the modern Paris that was already taking shape at the time. It is also interesting to note that Paris' status as a world city (embodied notably by the 1900 Universal Exhibition) was not called into question after the 1910 flood. However prospective studies show that such a flood today would be much more critical for the metropolis with its major economic and political stakes, supported by complex urban services. This analysis of interactions and interdependencies of urban networks allowed highlighting intrinsic fragilities of urban systems and their management in the event of a crisis (Toubin et al., 2012). In the context of the issues observed, the objective of the research was therefore to develop approaches and tools to help urban service managers to identify and implement the most appropriate characterize technical and organizational interdependencies to ensure the continuity of service despite disruption propagations in such critical infrastructure networks. The approach was built by integrating urban managers of the services areas of the City of Paris. This research draws up and analyzes the interdependencies of Parisian urban networks. It highlights certain dependencies, particularly those on electricity, telecommunications and transportation. The collaborative approach involved managers and forced them to think about strategies to mitigate or at least manage these interdependencies together. In addition, the collaborative process illustrated the need to move beyond isolated approaches (Fig.5) but rather to foster a common vision (Toubin et al., 2015). The collaborative approach can, for example, be used to illustrate the interdependencies between networks (Fig.5), the compartmentalized risk management between public and private actors in the city's services (Fig.5), and shed light on the major obstacles to the implementation of adaptation of the urban system to improve its overall resilience.

Figure 5. From individual operator resilience infrastructure diagnosis to interdependency mapping for risk management



improvement (Toubin et al. 2012)

The interweaving of scales as well of services, makes cooperation and transparency between operators and decision-makers indispensable for the construction of a more resilient city (Toubin et al., 2015).

4.3.2. Avignon case study

Seeking to analyze resilience through the three measurement indicators previously identified, a study in Avignon put forward the collaborative approach from a more exhaustive angle (Serre and Heinzlef, 2018). The approach developed emphasized collaboration between scientific experts and local actors. Building a common approach has made it possible to clarify the concept of resilience and translate it into a risk management strategy. This collaboration was carried out with the GIS service of the city of Avignon.

The collaboration crystallized at several stages of the research (Heinzlef et al., 2020b). After an analysis of the concept of resilience via a study of the scientific literature, a confrontation between scientific positioning and the knowledge of local actors took place. Indeed, it was necessary to reassess the envisaged indicators in light of the data used by the GIS department. After establishing the conceptual model of resilience with the indicators, the choice of processing tools was based on those used and known by the actors. The data processing and analysis was carried out at a regular frequency with the GIS department. As the spatial decision-support system is being built, a number of meetings with managers of critical infrastructures were held to test and validate the results. Thus, each stage was confronted with the reality of the actors, their understanding and their future use of the tool. This collaborative approach questioned the operationalization of the resilience and proposed an approach to meet these challenges. It appeared necessary to involve local knowledge, habits and practices in the construction of the tool to ensure its usefulness and subsequent use (Vanderlinden et al., 2017).

Collaborative strategies allow for a common knowledge to be built around a complex concept. This allows fuzzy concepts to be debated, dissected and operationalized. A spatial decision support system was designed with and for urban managers (Heinzlef et al., 2019). The challenge is to deepen this collaborative dimension by offering a platform for meetings, exchanges and local scientific-expert collaboration in order to promote the operationalization of resilience in risk management strategies.

These previous studies have helped to address some of the challenges of operationalizing resilience. Nevertheless, the obvious weakness of these studies is its multitude and the difficulty of local actors to integrate and understand it easily. The objective of this long-term work on the integration of the concept of resilience into risk management strategies is to envisage a living laboratory and an Information System Software structure that would bring together advances in the field and provide support for awkward resilience strategies and technical advances for scientists and local experts.

5. An observatory design: a long term and inclusive resilience monitoring and planning

The operationalization of resilience faces two major limitations:

- the difficult understanding of the concept itself;
- its application to the risk management dimension.

The challenge of integrating resilience into risk management is part of a complex and constantly evolving context: climate change and associated uncertainties. Faced with this climatic context, and with political, social, economic and territorial elements that evolve, there is an ever-increasing need for understanding and observation (Serre et al., 2019; Heinzlef et al., 2019b). It is therefore a question of understanding territorial systems in all their complexity by bringing together data and information produced by and for stakeholders. As a result, local actors are able to come together around issues that will require the implementation of development or management actions.

Observatories are tools whose objective is to observe (monitor, analyze, understand) on a portion of space representative of a territorial entity, the socio-environmental dynamics resulting from dynamic interactions of socio-economic and biophysical systems. They are a place of production, exchange, and sharing of information and knowledge that is sustainable. Observatories, at the interface between complex reality and knowledge (de Sède-Marceau and Moine, 2012), are therefore effective decision-making tools (Gayte et al., 1997; Heinzlef and Serre, 2020). Territorial dynamics and structures are changing very rapidly, due to political, environmental, demographic (Montgomery, 2008), spatial, organizational, governance (Mendizabal et al., 2018) transformations and other factors. These rapid changes lead to a growing need for information and observation in order to understand these complex territorial systems (de Sède-Marceau et al., 2009). Observatories are therefore beneficial tools for understanding, decision support tools for planners and elected officials, and a place for producing, exchanging and sharing information and knowledge over the long term (Heinzlef and Serre, 2020). To support territorial management, this observatory has to provide diagnostic functions to perform the evaluation of implemented actions. For instance, it may help to have a global perception of different issues on an urban project to measure positive and negative impacts on flood risk territories. It should also be associated with prognostic functions, in order to have the capacity to alert and guide managers in their decision-making process in the short and medium term. In addition, spatial decision support tools are often dependent on a specific territory and actors. An observatory is a spatial decision support tool on a larger scale, which can compare and confront several case studies, actors, experts, methodologies. There are currently various active observatories dedicated to the observation of the territory and space phenomena. They exist in the form of a virtual structure such as for the National Observatory of Natural Risks and the Territorial Observatory, etc. Their objective is to gather, analyze and disseminate data relating to territorial dynamics and disparities, and to allow everyone, professionals and individuals, to easily access data relating to natural risks produced by organizations for a better understanding of these phenomena and their impacts. However, these observatories combine neither scientific advances nor local knowledge, do not propose a double entity (virtual structure + living laboratory), and stop at the data acquisition part.

The future observatory would be a toolbox; developing, refining, and applying various methodologies to operationalize resilience. Initially conceived as a spatial decision support system, an evolution towards a living laboratory would be an essential transition. Composed of a university team and local actors, the human dimension of the observatory could enable *in situ* testing of resilience strategies and foster collaborative approaches (Fig.6). A test site will therefore be chosen according to the issues related to risks, and will serve as a crucible for innovation and as a prototype observatory.

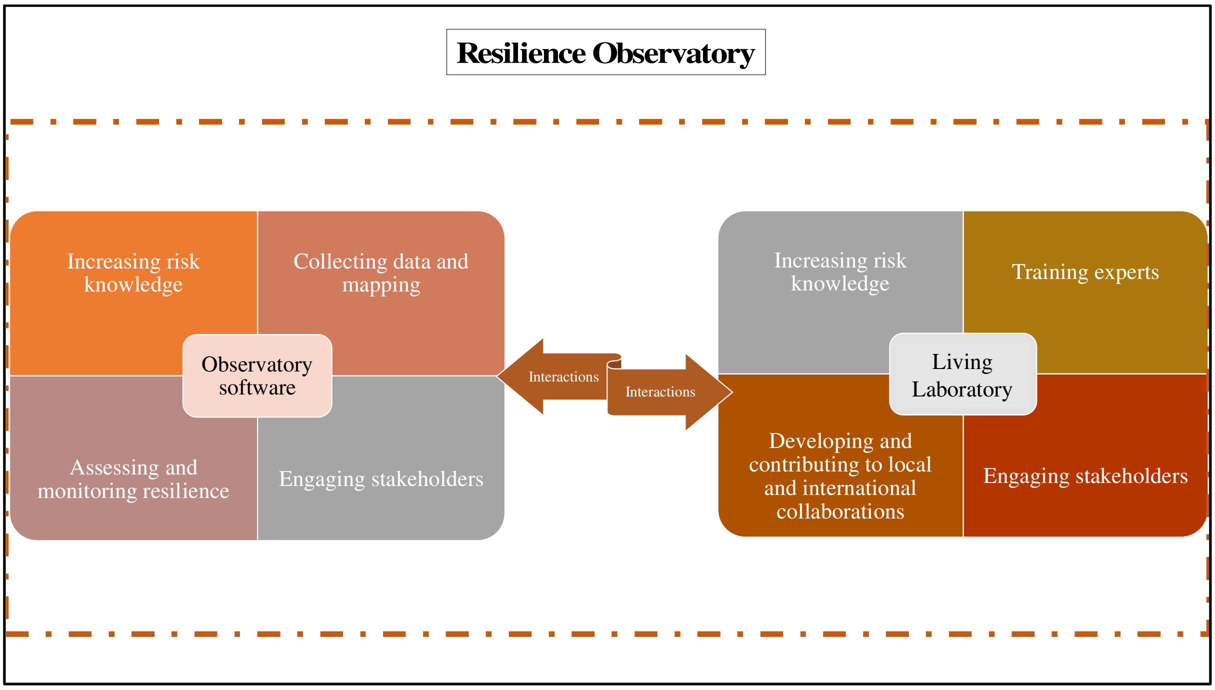


Figure 6: A prototype observatory

It is then a necessity to develop an observatory for reflection and action around the concept of resilience in the face of risk management. It is one important step to prepare territories, populations and local actors for climate disruption.

5.1. Increasing risk knowledge

The primary objective of this observatory is to produce, condense, multiply and transmit knowledge on risks and resilience. To this end, defining and assessing resilience at the local level is required in order to drive a decision support process. This step is built on previous research on the design of resilience indicators dealing with, urban, social and technical aspects. The challenge is to make them generic and reusable on different case studies and for various local actors in various contexts. The objective is to develop and deepen the pre-existing indicators in order to nuance the analysis with, in particular, a governance indicator (community investment of populations, action policies, dissemination of information concerning risks, land use planning policies, risk management, etc.).

5.2. Collecting data and mapping

Beyond enhancing the value of pre-existing open-access data, the observatory would be a key tool for producing new forms of data. Tools such as UAVs (Unmanned Aerial Vehicle) would contribute to improving knowledge on territories at risk in a very precise manner and in particular to define the adaptive potential of these territories. Moreover, the data acquired via UAVs would be processed by the Resilience Observatory and could provide a valuable decision-making aid for many decision-makers.

The interest of UAVs in risk management is manifold. Their low-cost use ensures the widespread adoption of these tools (Serre et al., 2019). In addition, the automation of the tool can allow a repeatability of measurement which would be valuable in the monitoring of space evolutions leading to a more accurate and complete spatio-temporal monitoring. Finally, such tools are advantageous for accessing territories that are difficult for individuals to access. In addition to data acquisition, data processing and visualization will be an important area of development, particularly with geo-visualization techniques.

5.3. Engaging stakeholders

Since the 1990s, there has been a growing interest in the geospatial dimension of data, particularly in reason of the dissemination of geographic information systems and technologies (Andrienko et al., 2007). These technologies include geographic information systems (GIS), low-cost GPS equipment and satellite imagery, among others (Appeaning et al., 2018). Recently, software for the collection, storage and analysis of geo-referenced information is becoming increasingly user-friendly. Thus, development practitioners, activists and researchers are turning to GIS to increase the participation of local people in planning processes at the local or regional level, and to facilitate the dialogue between policymakers and communities on the ownership, use and control of natural resources. As a result, a growing number of community-based initiatives are emerging to collect, organize, visualize and geo-reference the knowledge of local people using what is generally referred to as participatory GIS. Participatory GIS is actually an approach born out of the combination of participatory learning and action methods and traditional GIS. It is based on the integrated use of tools, methods, technologies and systems ranging from simple map sketches to participatory three-dimensional modelling, common interpretation of aerial photos and the use of GPS and various GIS applications. Through participatory GIS, local people's knowledge is translated into two- or three-dimensional, physical, open-access maps and used as interactive tools for geospatial learning, information exchange, decision support, natural resource use planning and advocacy.

The observatory would therefore integrate a kind of participatory GIS for local actors to promote understanding (van de Ven et al., 2016), perception and integration of the concept of resilience into risk management strategies.

5.4. A Pacific resilience observatory

A research project led by the IRD and the CNRS has been set up in order to respond to the challenges of operationalizing resilience in French Polynesia. The objective of this Pacific Island Long Term reSilience (ILOTS) project is to initiate reflection on a Resilience Observatory in order to work on the limits and biases of the concept and its operationalization (Serre, 2019). Building a Resilience Observatory prototype in the Pacific islands makes sense in light of the risks to which they are exposed. The French overseas islands have a high level of hydrometeorological hazards and often inadequate risk management methods, tools and strategies. A 2014 interministerial report also highlights the difficultly of sharing responsibilities between national and local authorities with regard to poor risk management processes, with one crucial point in particular: the national risk observatory does not cover the overseas territories. At the same time, local authorities do not seem to be willing to fully engage in risk management, with the exception of hurricane-related issues, due to the cultural awareness of the population in the face of these hazards. A more critical problem is the lack of control of land and urban development by local authorities. The report also contains recommendations to improve risk management strategies in overseas regions such as the ambition to transform overseas territories into territories of innovation for risk management by engaging the scientific communities and to make urban planning a non-structural measure to reduce risks by taking into greater account of the impacts of climate change.

The observatory project will therefore make it possible to design a framework to meet the needs in terms of scientific, technical, social and territorial advances. Thus, the observatory prototype is innovative at several levels; responding to an assessed need (intensity and recurrence of disasters) with a solution that does not yet exist, carrying out the observatory with new models to assess the level of resilience to floods in a multi-scale perspective (space and time) and using open source tools, data and solutions as much as possible in order to minimize the cost of the observatory and maximize its future use. This observatory project would therefore be justified from an economic point of view. The emphasis on open source tools and the use of existing data that is not very valuable or not cross-referenced in an enriching way to operationalize resilience makes the cost of the tool almost non-existent for local actors. The current costs are linked to the research teams but only financed by the scientific projects of the academic team. Subsequently, it will be a question of training local actors in the use of the tool. For these reasons, a prototype toolbox such as an observatory takes on its full meaning in the pacific island territories.

Conclusion

Faced with the challenges of climate change and the uncertainties related to risk management, the concept of resilience has emerged as an innovative and promising way to prepare territories, populations and territorial actors. However, this concept is still unclear and difficult for local actors to understand and operationalize.

This article highlights two methodologies aimed at addressing the limitations of integrating the concept of resilience into risk management strategies: a technical-functional methodology and a more organizational one. The technical approach has the advantage of responding to critical infrastructure issues and interdependencies that increase territorial vulnerability. However, this approach is limited because it reduces territorial complexity to critical infrastructures. The organizational approach tends to respond to these limitations by proposing to analyze the different elements that make up the territory and participate in increasing and/or reducing resilience. While these two approaches make it possible to advance in the clarification and use of the concept by local stakeholders, the multitude of tools, their temporal limitation of use and their very localized action make these methodologies limited and too localized.

On account of this observation, a global tool project has been envisaged; a resilience observatory. A resilience observatory would make it possible to develop a comprehensive human and computer-based tool to condense, compare, develop and bring out different methodologies for operationalizing resilience. Based on several pillars (defining and measuring resilience, acquiring, processing and visualizing data, promoting and developing the integration of local stakeholders in the process of cultivating resilience, etc.), the observatory would make it possible to reconcile local, international and scientific advances in order to provide a structure for reflection and action to operationalize resilience. In addition, such a structure would make it possible to develop tools and methodologies that address resilience in a comprehensive and exhaustive way, but also over a long period of time. Indeed, the monitoring, acquisition and use of past and current data would make it possible to apprehend the territory, the risks and the resilience over the long term in order to adapt risk management strategies in the face of a spatial but also social trend. This temporal dimension is essential in order to allow appropriation, to consider the concept of resilience and to promote decision support. Such a prototype has been launched and tested in the Pacific and more particularly in French Polynesia in order to serve as a reference case study to develop this kind of observatory on an international scale in the future.

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