GIS development for urban flood resilience

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Abstract

In France, as in the rest of Europe, river floods have been increasing in frequency and severity, there are more and more instances of rivers bursting their banks, aggravating the impact of the flooding of areas supposedly protected by flood defenses. These circumstances oblige us to manage flood risk by integrating new concepts like urban resilience design. Definitively, our goal is to reduce flood risk by managing vulnerability issues of flooded areas to achieve flood resilient cities. A first analysis of city needs of decision-making tools showed that no tools to prioritize recovery actions are available. This tool needs to integrate some models and indicators to be efficient: an urban systemic model of the city; resilience indicators; failure and recovery scenarios. A first prototype sketch was designed but it needs to integrate these models and indicators. That is why, as part of a future PhD thesis, this tool will be developed to be used directly by decision makers and communities.
Keywords: resilience, GIS, indicators, urban systemic model, urban networks, safety methods.

1 Introduction

In France, as in Europe, river floods have been increasing in frequency and severity [1] and there are more instances of rivers bursting their banks, aggravating the impact of the flooding of areas supposedly protected by flood defenses. Moreover, climate change is expected to exacerbate the frequency and intensity of hydro meteorological disaster [2]. Despite efforts made to maintain the flood defense assets, we often observe levee failures leading to finally increase flood risk in protected area. Furthermore, flood forecasting models, although benefiting continuous improvements, remain partly inaccurate due to

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uncertainties arising all along data calculation processes. So, zero risk does not exist and it would be very dangerous to believe otherwise.

In the same time, the year 2007 marks a turning point in history: half of the world population now lives in cities (UN-Habitat, 2007). Moreover, the total urban population is expected to double from two to four billion over the next 30 to 35 years (United Nations, 2006). This growing rate is equivalent to the creation of a new city of one million inhabitants every week, and this during the next four decades [3]. So, this quick urban development coupled with technical failures and climate change has increased flood risk and corresponding challenges to urban flood risk management [4, 5]. These circumstances oblige to manage flood risk by integrating new concepts like urban resilience.

That is why the main aim of our researches is to integrate the increasing demand for more houses and other buildings with the increasing need for more and better flood risk management measures. Our goal is to reduce flood risk by managing issues and vulnerability of flooded areas to achieve urban resilience face to flood events. In this context, a first analysis of city needs about decision making tools shows they do not have tools available to help them to prepare and optimize recovery actions whereas of course they are interested in having them. Such as tool should assist urban planners in proposing several failures and recovery scenarios and their impact on the urban areas. This decision software will be based on GIS, because GIS allows capturing, managing, analyzing and displaying all spatial data as well as flooding information. First, during normal period it will help to identify critical infrastructures and to prepare emergency planning thanks to resilience assessment. Secondly, after flood events this tool will help to recover.

A first sketch was designed. With this first sketch, currently still under development, we hope to illustrate GIS benefits to city partners to show how such a tool allows improving urban resilience. In fact, the main goal of the GIS prototype was to check the technical feasibility of such a decision tool. Of course, it is only a first step, but specifications have been studied with the aim to synthesize the needs of decision makers according to service functions.

The first part of this paper introduce resilience concept to well understand the importance of this concept to manage flood risk. In a second part, we are proposing an urban systemic model in order to understand relations between systems for assessing resilience. Finally, this paper presents the use of safety methods to model urban system dysfunctions during flood and to produce disturbance scenarios. It’s the first step to be able to produce recovery scenarios needed by city planners.

2 Resilience: a key concept for flood risk management

Vulnerability is a complex concept to define [6]. However, this concept is crucial to understand and to define risk. Indeed, the risk can be considered as the intersection of hazard and vulnerability. Disaster management has typically focused on analyzing the hazard. Yet, river floods have been increasing in frequency, so researchers and few decision makers recognize the need to analyse not only the hazard but also the vulnerability to each specific hazards. That is why disaster management has been moving away from solely emergency response, initiated during and after a flood event, toward mitigation and preparedness, initiated before an event, in order to reduce impacts more effectively [7–9]. So, nowadays mitigation decreases the losses from natural hazards by reducing our vulnerability or by reducing the frequency and magnitude of causal factors [10].

Many researchers emphasized the importance of vulnerability assessments, yet relatively few have developed methods to assess vulnerability empirically [9]. In their vulnerability model, vulnerability (V) is based on three primary variables:

- exposure (E),
- sensitivity (S),
- adaptive capacity (A).

For instance, higher hazard exposure and higher sensitivity lead to higher potential impacts and higher vulnerability, eqn (1). Higher adaptive capacity leads to lower vulnerability, eqn (1).

$$V = (E + S) / A. \qquad (1)$$

In another study vulnerability assessment is based on three similar variables: exposure, resistance, resilience [11]. First sensitivity and resistance are both quite similar; secondly resilience is a key to enhance adaptive capacity [29]. So, on one side when systems resilience is improved, systems vulnerability decreases, on the other side erosion of resilience causing vulnerability [12]. For these reasons resilience has emerged recently as a key concept to manage flood risk.

Resilience can be considered as "*the magnitude that can be absorbed before the system changes its structure by changing the variables and processes that control behavior*" [13]. This definition works for all ecosystems but also for social systems like city. So to study the urban flood resilience we need to consider the city like a system.

However, the link between creating resilience day-to-day operations and having a resilient crisis response and recovery is typically not well understood by organisation [14]. That is why decision makers need tools to help them to decide best recovery actions after flood events, but also to help them to prioritize actions before crisis with the use of different scenarios.

This tool to aid cities to prepare/recover after a flood event needs to integrate some models and indicators to be efficient. Especially:

- urban functional model of the city
- resilience indicators
- failure and recovery scenarios

3 An urban systemic model of the city

The principle is to study a city like a system, especially like a complex one. Indeed a system is an "*autonomous entity with regard to its environment, organised in a stable structure (identifiable in the course of time), constituted by interdependent elements, whose interactions contribute in maintaining the system structure and making it evolve*" [15]. As illustrated in the literature [16], Sanders [17], Beaujeu-Garnier [18] a city appears as a set of components interconnected by networks, so it seems that the system definition works for the city. Moreover, the city can be viewed as a system within a system of cities [19] (multi-scale approach introducing a new level of complexity), a fact that flood management has to take into account.

In this framework, a systemic model has been designed to study cities and to model their functions. In this model, the city is composed by different elements such as population, companies, public infrastructures, housing and networks, fig. 1.

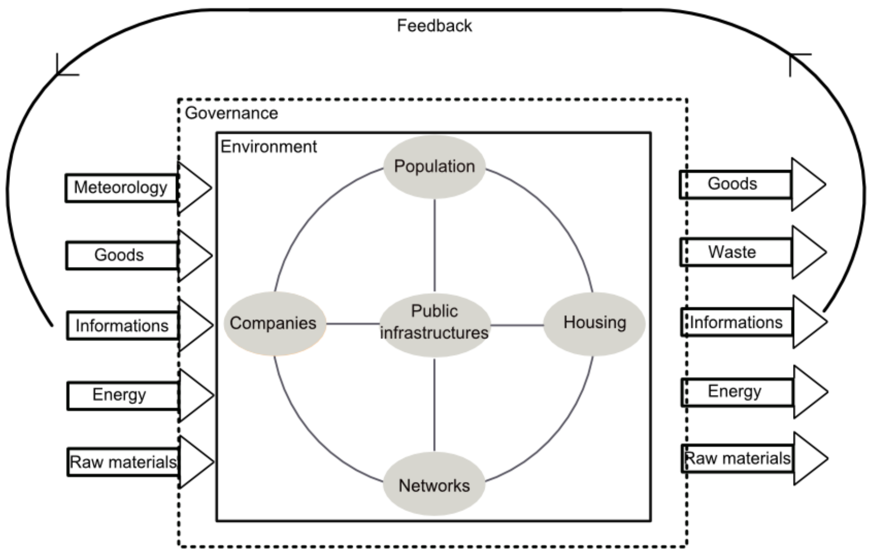

Figure 1: Urban systemic model.

Here networks include all infrastructures and facilities necessary for its operation. These components are supported by the environment and they are organized by governance. Here governance refers especially to city administration, regional government and state government. The system relations with its environment are characterized by exchanges with other cities (raw materials, manufactured goods ...) and of course the waste produced by activities and population. In this system, it is important to distinguish inputs from outputs because outputs will influence (involve) future inputs (principle of feedback), fig. 1.

Using a systemic approach to analyse urban flood disturbance we discern economic, population, environmental, governance, network and housing disturbance. For each disturbance proposed we should define indicators to determine the city performance during the flood. These indicators should take into account the importance of the system dysfunctions, the intensity of physical damage of the system and the duration of the dysfunctions.

A flood event is characterized by the hazard and the environment characteristics. Flooding spreads in urban areas through the networks (especially the road network) and thus it can reach all the other urban components. Public infrastructures and their managers are directly involved in crisis management, while companies, population and housing may be affected by several scenarios. Meanwhile both the inputs and outputs of the system are disturbed, fig. 2.

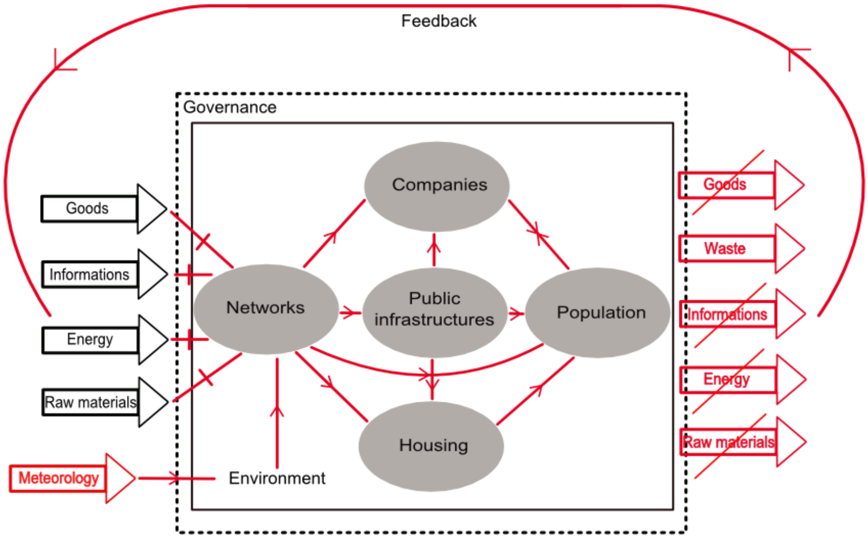

Figure 2: Urban systemic model during flood events.

4 Safety methods: urban network system performances

The urban model presented highlights networks importance, especially during the flood. Indeed, networks can be regarded as the "flood gateway" and as "the risk gateway". Thus, we will focus on these technical systems that spread the risk through the city. Among network systems we have to include: energy, transportation, telecommunication and water networks.

Networks affect the well being of the people and the smooth functioning of services and, more generally, of economical activities [20]. Yet, multiple networks that innervate the city are particularly sensitive to flooding, through their structures and geographic constraints. So, to analyse urban networks system performances we propose to use safety methods. These methods will allow better understanding how a city functions during flood event. We use tools developed in Operational Safety for modeling complex systems and representing the organic links between the sequences of failures in the structures [21]. The functional model representing the mechanisms is built up in the three stages shown schematically in figure 3. In this article we just present the main lines of this model.

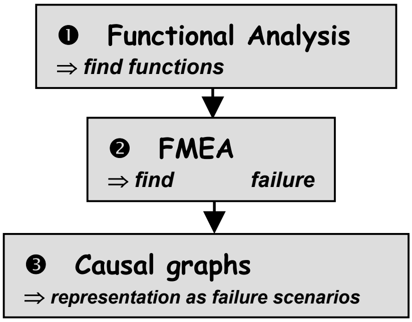

Figure 3: Principles of basic failure scenario model.

4.1 Functional analysis

The first method to be used in an Operational Safety exercise is a functional analysis to understand and synthetically describe how a system functions. The functional analysis defines the boundaries of the system, its environment, and the functions it provides [21]. A functional analysis of networks systems was carried out with detailed functional analysis of each network. First, an external functional analysis was carried out describing interactions between the system and its environment. Moreover, this external functional analysis allowed defining boundaries of the systems. This analysis directly uses urban systemic models. Secondly, an internal functional analysis was carried out, thanks to three Functional Diagram Blocs (FDB): contact, hydraulic flow and vulnerability, fig. 4. These FDB mainly allow describing interactions between the system and its environment and also interactions between the system and its components according to the source of the interaction (contact, hydraulic flow and vulnerability).

From these diagrams five main functions were determined for network systems:

- to ensure continuity of services;
- to resist to hydraulic flows;
- to ensure hydraulic flows;
- to resist the mechanical pressure;
- to enable the functioning of other urban components.

Then each component was associated to the corresponding functions. Thus FMEA was carried out.

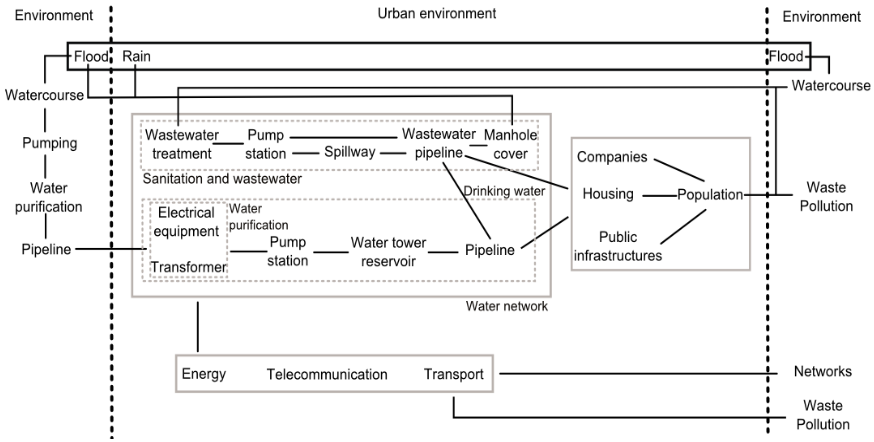

Figure 4: FDB contact of water networks.

4.2 Failure mode and effect analysis (FMEA)

The Failure Mode and Effect Analysis (FMEA) is one of the routine Operational Safety methods used in most industries, including aerospace, nuclear, and automotive. FMEA is an inductive method for analyzing potential system failures. It focuses systematically on each component in the system to determine its failure modes (a failure mode is the non-performance of a function under system conditions: absence, loss, deterioration or untimely operation of a function, and the effects and consequences thereof), and their causes and effects [22]. The FMEA analysis is performed with a worksheet which is the principal feature of an FMEA.

First, FMEA requires breaking down the system into components (structural analysis). Then it is necessary to identify the functional structure of the system and how the components contribute to functions: it explains why a Functional Analysis has to be built up upstream. Then FMEA requires defining the failure modes for each component and finishing perform analysis for each failure mode of every component and recording results in a table. The two first steps have already been described above in the functional analysis and the last two steps allow completing the FMEA table, table 1.

Table 1: Example of FMEA table.

Network	Component	Functions	Dysf	Causes	Effects
Water	Pipeline	Ensure continuity of service	Function	Under design Break Congestion	flooding
		Resist hydraulic flow	Function	Water overload	Break Congestion

4.3 Events trees

After compiling the FMEA data, we can determine the most important failure modes of the systems, their causes and their effects. So, using the FMEA, the failure mechanism model had been defined, and failure scenarios had been designed thanks to events trees. The events trees analysis was developed in early 1970 for risk assessment of nuclear power plants. It allows estimating probabilities of occurrence of accidental sequences. This method is particularly used in the post-accident analysis to explain the results observed in a system failure. Here we are just using the method without quantitative aspects, but this model involves and underlying domino effect induced by networks failure. Indeed, infrastructures and systems do not exist in isolation of one another – telecommunication networks require electricity, as do the sewerage systems. Transportation networks often use sophisticated computerized control and information systems, the generation of electricity requires fuels, etc [23].

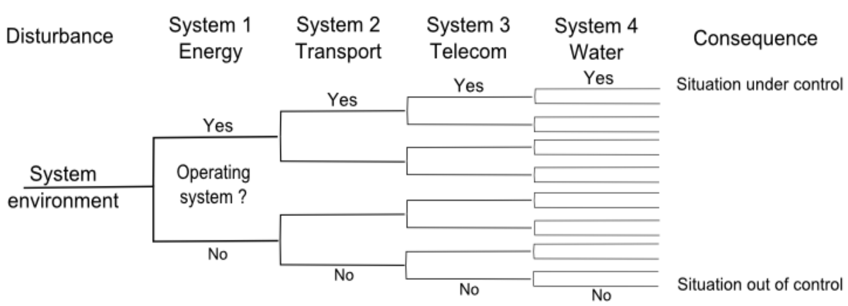

Figure 5: Use of the tree method.

For example, energy networks are very aggressive (others networks depend on energy networks) compared to other networks. During a crisis, it seems fair to ensure the proper functioning of these energy networks before the others. In case of failures, the rehabilitation will require the proper functioning of transport and communication networks. So, dependency and interdependency between infrastructures will always have major effects on the amount of damage and the recovery period of infrastructural failures and thus on the resilience of the infrastructural systems [24].

We design networks systems failure scenarios by linking failure causes to failure modes, and then to failure effects. In this way, the failure mechanisms are modelled as series of functional failures representing the relevant physical processes taking place within the system and leading to loss or deterioration of function. These scenarios are the first step toward recovery scenarios design.

5 Conclusion

In the current discussion on flood resilient cities a strong emphasis is placed on improving the flood performance of buildings, but the city has to be considered as an entity with different systems and vital functions and not merely as a set of concrete buildings [24]. It is exactly our approach in this paper with our city model and the study of the disturbance of critical infrastructures (here just the networks). To better respond to post disaster activities geographic information system (GIS) technology provides a logical tool for integrating the necessary information and contributing to preparedness, rescue, relief, recovery and reconstruction effort [25, 26]. GIS is seen as a necessary tool in the area of emergency response [27, 28]. Yet, resilience requires looking beyond lonely emergency response in order to optimize recovery after a flood event thanks to preparedness and resilience assessment.

Nowadays, we have a first prototype sketch. We have also designed an urban systemic model and it firsts applications thanks to safety methods. These applications to one component of the city system (the networks) must be expanded to other city components. However, we better understand how networks operate during a flood event. Moreover, we are able to produce disturbance scenarios of these systems and also of the whole city system, because these systems can be considered as the food gateway. These results in combination to future network performance indicators will allow assessing city sensitivity to flood. We have now to focus on the post-flood analysis.

First, this tool will implement the urban systemic model for the data integration and scenarios. This urban systemic model implementation with GIS is one of the critical technical points. Secondly, the tool will implement the future resilience indicators thanks to network performance indicators (using graph theory). Here, it will be possible to propose few recommendations. So decision maker will be able to prepare and optimize recovery, making their city more resilient day to day.

In recent years, resilience has become a central concept of risk management. This concept has emerged because a more resilient system is less vulnerable to risk and, therefore, more sustainable. This paper proposes methods to improve resilience using spatial analysis. Developments are required to make this tool efficient: failure and recovery scenarios, and resilience indicators have to be developed. These researches are the first steps toward the development of a GIS tool to optimize preparedness and recovery after a flood event, thanks to an urban systemic model and the use of safety methods to underline critical components in order to produce disturbance scenarios.

References

[1] Szöllösi-Nagy A. & Zevenbergen C. *Urban flood management*, Introduction, pp 1-10, 2005.

[2] IPCC (Intergovernmental Panel on Climate Change), *Climate change 2007: The IPCC fourth assessment Report, Summary for Policymakers*, www.grida.no/climate

[3] Flood resilience Group, FRG Overview, www.floodresiliencegroup.org/frg/
[4] Ashley, R., Blanksby, J., Chapman, J., Zhou J. J. *Towards Integrated Approaches to Reduced Flood Risk in Urban Areas*. In: Ashley, R., Garvin, S., Pasche, E., Vassilopoulos, A., Zevenbergen, C. Advances in Urban Flood Management, pp. 415- 432, 2007.
[5] Nie, L.M., Lindholm, O. and Braskerud, B.C. *Urban flood management in a changing climate*. J. of Water by Norwegian Water Association, Vol. 2, pp. 203-213, 2009.
[6] Ledoux B. *La gestion du risque inondation*, Editions Tec&Doc, 770p, 2005.
[7] Wilhite D.A. "*The role of the government in planning for drought: Where do we go from here?" Planning for drought: Toward in societal vulnerability*, D.A. Wilhite and W.E. Easterling (eds.), pp 425-444, 1987.
[8] Hooke W.H. *U.S. participation in international decade for natural disaster reduction*, Natural Hazards Review, ASCE, pp 106-133, 2000.
[9] Fontaine M.M. & Steinemann A.C. *Assessing vulnerability to natural hazards : Impact-based method and application to drought in Washington state*, Natural Hazards Review, ASCE, pp 11-17, 2009.
[10] Rose A., Porter K., Dash N., Bouabid J., Huyck C., Whitehead J., Shaw D., Eguchi R., Taylor C., McLane T., Thomas Tobin L., Ganderton P.T., Godschalk D., Kiremidjian A.S., Tierney K., *West C.T., Benefit cost analysis of FEMA hazard mitigation grants*, Natural Hazards Review, ASCE, pp 97-110, 2007.
[11] Dauphiné A., Provitolo D. *La résilience : un concept pour la gestion des risques*, Annales de géographie n° 654, pp. 115-125, 2007
[12] Folke C., *Resilience and sustainable development: Building adaptive capacity in a world of transformation*, Environmental Advisory Council to the Swedish Government, 2002.
[13] Gunderson L.H. & C.S. Holling, *Panarchy: Understanding Transformations in Human and Natural Systems*, Island Press, 508 p., 2002.
[14] McManus S., Seville E., Vargo J. & Brunsdon D., *Facilitated process for improving organizational resilience,* ASCE, Natural Hazards Review, pp 81-90, May 2008.
[15] Pumain D., *La dynamique des villes*, Editions Economica, 1982
[16] Pumain D., Sanders L., Saint-Julien T. *Villes et auto-organisation*, Economica, 191 p., 1995
[17] Sanders L., « Système de Villes et synergétique », col. Villes Ed. Anthropos-Economica, 274 p, 1992.
[18] Beaujeu-Garnier J., G*éographie urbaine* , cinquième édition, édition Armand Collin, 1997.
[19] Berry B.J.L., *Cities as systems within systems of cities*, Papers of the Regional Science Association, pp. 147-163, 1964.
[20] Etablissement public Loire, *Etude préalable à la réduction de la vulnérabilité des réseaux liée aux inondations en Loire moyenne*, 2006
[21] Modarres, M., *What every engineer should know about reliability and risk analysis*, New York, Marcel Dekker Publisher, 1993.

[22] Hartford. D.N.D., Beacher. G.B., *Risk and uncertainty in dam safety*, CEA Technologies Dam Safety Interest Group, London, Thomas Telford Eds, 2004.
[23] Syncera, *Quick Scan Halve Meter Ram,* In opdracht van het Ministerie van Verkeer en Waterstaat, DG-Water, 2007.
[24] Anema, K.A. MSc, *A scoring system for the resilience of critical infrastructure and their interdependent networks in cities*, cost22, 7 p, 2009.
[25] Gunes A. E., Kovel J.P., Using GIS in emergency management operations, J. Urban Plann. Dev., 126(3), pp 126-149, 2000.
[26] J. Lembo Jr A., Bonneau A., D. O'Rourke T., *Integrative technologies in support of GIS-based postdisaster response*, Natural Hazards Review, ASCE, pp 61-69, 2008.
[27] Carrara A., Guzzetti F., *Geographical information systems in assessing natural hazards*, Kluwer, 1996.
[28] Ware J. I., Geospatial data fusion: Training GIS for disaster relief operations, 2001.
[29] Resilience alliance, http://www.resalliance.org/565.php